Evaluation of Fly Ash in Concrete

Fly ash, the collected powder from flue gases, consists mostly of fused ash particles, with some unburned granules of coal—the result of combustion of powdered coal in modern boilers. In the past 25 years this waste product has become increasingly expensive to dispose of. It is estimated that about $17,500,000 per year is spent for its disposal. This has resulted in efforts to develop useful applications that will eliminate the disposal problem, and will eventually turn a costly liability into an income-producing asset.

While many uses have been tried and discarded as being uneconomical, uncompetitive, or impractical, and sundry other applications have been found feasible, but do not utilize significantly large quantities of fly ash, its use in concrete work has found favor all over the industrial world where fly ash disposal is a problem. The use of fly ash has a potential that, if fully exploited, might become a solution which could eventually turn a $17,500,000 expenditure into an equivalent amount of revenue from its sale, thus an eventual gain of approximately $35,000,000 annually.

Applications that may offer considerable disposal potential such as soil-lime stabilization (the only practical and economic method known for stabilizing heavy soils), manufacture of brick, special building blocks (not involving portland cement), and other minor uses are not covered in this study.

Bituminous Concrete and Bituminous Products

One of the phases of concrete in which fly ash has proven satisfactory is dense graded high type bituminous concrete and bituminous product mixes. In this application, fly ash as a filler material replaces the presently used limestone dust, or other finely powdered material.

Used in this manner, it has a potential of utilizing larger amounts of fly ash than the asphalt in the mixes. Full benefit of this possibility has not been realized, principally because of the entrenchment of the limestone dust industry, and lack of concerted promotion. Yet, fly ash can generally be delivered to the asphalt plant at a much lower cost than the limestone dust or other fillers. Detroit Edison Company appears to be the principal fly ash producer to take advantage of this application on a large scale.

A conservative estimate of the potential use that could be developed in this field is about 1,000,000 tons of fly ash per year.

Lightweight Aggregate

The lightweight aggregate field, another of the possible uses of fly ash in concrete, is in the opinion of the writer the largest potential. This, because the use of lightweight concrete is increasing at an extremely rapid rate, and because every cubic yard of this lightweight concrete utilizes about one ton of lightweight aggregate (a little less for the structural grade and more for building blocks).

In comparison, a cubic yard of bituminous concrete contains 250 to 400 pounds of fly ash filler, while a cubic yard of regular portland cement concrete will have 100 to 150 pounds of fly ash. These figures will vary widely with the materials and mix porportions, but are reasonable averages for this comparison.

The estimated annual lightweight aggregate production is between 8,000,000 and 10,000,000 tons. If fly ash lightweight aggregate could eventually capture ⅓ of this market, it would mean a potential disposal of 3,000,000 tons of fly ash. The basic scientific principles and processes have already been worked out. Additional research and development are needed to make this a reality.

Portland Cement Concrete

The best known use of fly ash in concrete is as an additional ingredient in portland cement mixes, resulting in a concrete with improved properties, and in most instances reduced cost. Very frequently some savings in cement can be effected. Among the improvements that fly ash imparts to concrete mixes are:

Pozzolanic properties
Lower water requirement
Improved workability
Reduced segregation
Reduced bleeding
Somewhat retarded time of set (well within acceptable limits)
Lowered heat of hydration
Reduced volume change
Increased extensibility and plastic flow at early ages (thus accommodating early shrinkage with less cracking)
Improved molding qualities
Adequate strength (varies with mix and fineness of fly ash)
Increased modulus of elasticity
Reduced permeability
Reduced alkali-aggregate reaction
Reduced cement-aggregate reaction (in sand-gravel aggregate areas)
Adequate freezing and thawing resistance (with air entrainment and proper curing)
Increased resistance to sulfate action

Occasional doubts are expressed regarding the resistance of fly ash concrete to salts, to abrasion, and to freezing and thawing, when the concrete is not cured adequately. With no reliable information available regarding these factors, research is required to determine the facts, and develop solutions where necessary.

As an ingredient in concrete mixes, fly ash can be used in amounts varying from 100 to 150 pounds per cubic yard. This use is very well established, and the only drawbacks are the handling and mix control of an extra and somewhat difficult to manage material, and the reputed low early strength. These problems can be solved with present-day knowledge, namely, through proper equipment for handling and batching, and improving the early strength by the use of larger proportions of fly ash, addition of proper trace chemicals, addition of water reducing admixtures, or intergrinding of fly ash with cement clinker.

Building blocks, precast, and prestressed concrete members represent a specially attractive field for the use of fly ash in portland cement, because handling of materials is centralized in a plant and is therefore less of a problem, and because the high temperature curing used in these operations develops the higher early strengths. Advantages of fly ash to these operations are reduced wear on the forms and equipment, better molding qualities, and reduced costs. Thus, this field profits not only from the regular advantages of fly ash in portland cement concrete, but has the added benefit that it does not suffer from the disadvantages, and is therefore an excellent potential outlet.

Fly ash should be considered as an ingredient in concrete imparting certain desirable properties, and not as a "replacement" of cement, as the latter may imply to some, that fly ash is "not as good" as cement. As an additional ingredient, the practical usefulness of fly ash depends on the distance of the source from the large project or the concrete products plant. This potential can be increased manyfold by intergrinding the fly ash with the cement clinker at the cement mill, resulting in a single cementitious product that does away with handling and batching an extra ingredient, and at the same time improves the early strength. This makes it use feasible on every small job, and thus opens up a tremendous field. There has been some resistance to the production of such a cement in this country, but the reports from Europe are very encouraging. Study of the European methods, research and development to adapt them to American conditions, and some method of overcoming the resistance against the production of such a material are needed to permit the realization of full advantage of this development.

Another use in concrete, that has not received much attention in the United States, is as a raw material in the manufacture of portland cement. In this application it competes with other sources of silicates, aluminates, and iron as raw material compounds.

Thus, in addition to minor uses such as grouting mixtures, and sealing of oil wells, there are at least four major fields having large potential for the use of fly ash in portland cement concrete:

1. Light weight aggregate
2. An ingredient in ordinary concrete and precast products
3. Interground with cement clinker to produce a better cement
4. As a raw material for regular portland cement

Research and Development

Research and development have been the cornerstones of industrial advancement and growth. The largest growth has occurred in industries that have engaged in the most active and extensive research. Fly ash is no exception, if its use is to be broadened and extended, and if the large disposal cost is to be eliminated and eventually turned into a revenue. Research on several fronts is clearly indicated by this study, to remove the doubts about certain properties of fly ash concrete, to solve problems, to develop processes, and to accumulate data needed for the proper utilization of the material. The most important are:

1. Research and development work on lightweight aggregate in the light of what has been done in Europe and in this country to adapt processes to American industrial conditions, and to develop background data of its properties and uses as compared to existing lightweight aggregates. The use of fly ash lightweight aggregate in bituminous mixes needs investigating also.
2. Research and development work on the intergrinding of fly ash with portland cement clinker, or with slag and portland cement clinker (in the light of European experience), to permit the elimination of the handling of fly ash as a separate material, thus extending its advantages to the small job and at the same time improving the early strength that has been a deterrent to its use in many structural applications.
3. Research regarding the resistance of fly ash concrete to freezing and thawing when subjected to short, moist curing periods (which are the rule), the resistance to abrasion (which is important in highway work), and the resistance to salts for de-icing highways in winter. Solutions to these problems are probably closely tied up with the improving of early strength through intergrinding, inasmuch as present doubts have resulted from comparing fly ash concrete with plain concrete on the "equal age" basis, rather than on

an "equal strength" basis. The latter becomes realistic with present-day methods of improving early strength. It may very well turn out that these doubts, concerning fly ash concrete, will completely vanish as it becomes more and more practical to compare fly ash concrete with plain concrete on an "equal strength" basis.

4. Research and development work on the use of fly ash as a raw material in cement manufacture to help broaden its present-day limited use in this field.
5. Research regarding the high temperature curing as it applies to building block, and various precast and prestressed units, is needed to determine the best cycles for developing the optimum pozzolanic properties, thus making it possible to increase this field of fly ash utilization.

It has been estimated that about $75,000 is being spent each year on fly ash research. Most of this is carried on sporadically by individual electric generating companies, or individual fly ash distributors. Much of this effort overlaps, and thus incurs an inefficient use of funds. For the research recommended, an over-all coordinated program is needed—one with sufficient funds to push research at a rapid pace, since the faster the information is gained, the earlier the reduction in disposal cost. Properly planned, coordinated, and directed research would in a few years result in information that would clarify the doubts and provide knowledge on the questionable properties and applications of fly ash, which have been revealed by this study.

As estimated, the eventual potential total gain for the fly ash producers is of the order of $35,000,000 per year. The increased use of fly ash as a result of such research is estimated to result in a gain of another $35,000,000, divided between the distributors and the users. The creation of wealth equal to four times the disposal cost cannot be ignored. It is a challenge to everyone concerned.

● FLY ASH is the very fine residue from the burning of powdered coal, collected in the stacks of power plants by mechanical means or by electrical precipitators, or a combination of the two (43, 102, 111, 180, 205, 206). In most instances, the fineness of fly ash equals or exceeds that of portland cement.

Fly ash consists for the large part of solid or hollow spherical particles of siliceous and aluminous glass, with small proportions of thin-walled, multi-faced polyhedrons called "cenospheres," of reddish particles high in iron, and of irregularly shaped, relatively porous carbon or carbon-coated particles (53, 102, 111, 119, 152, 194, 205, 226).

The fineness, chemical composition, and physical properties of fly ash vary depending on the source of coal, method of burning, combustion equipment, variation in load on the boilers, and methods of collection (16, 17, 43, 65). Thus one can expect relatively large variations between plants, but the product of one plant, using one source of coal and operating on a steady load, is generally uniform.

Many chemical and physical analyses of fly ashes are found in the literature, most of which fall within the following ranges (3, 29, 101, 135, 158, 205, 226):

		Percent
Silica,	SiO_2	28.1 - 51.26
Alumina,	Al_2O_3	15.12 - 34.04
Iron Oxide,	Fe_2O_3	3.86 - 26.43
Lime,	CaO	1.00 - 10.59
Magnesia,	MgO	0.55 - 1.91*
Sulfur Trioxide,	SO_3	0.23 - 3.59**
Ignition Loss		0.56 - 31.56

Specific Gravity	1.88 - 2.84
Passing No. 16 Sieve	99.40 - 100.00
Passing No. 325 Sieve	62.4 - 97.9
Fineness, Blaine (square centimeters per gram)	2,007 - 6,073

*Usual range, but occasionally it is found in traces only and at times in excess of 3 percent.

**Usual range, but occasionally it has been found as high as 12 percent. One case of a cyclone type burner is known to have produced fly ash with 17 percent SO_3.

The Fe_2O_3, Al_2O_3, and SiO_2 tend to concentrate in the finer particles, while the carbon predominates in the coarser grain sizes (152).

The color varies from light to dark gray, and in some cases is brownish. Generally, the darker the color, the higher the carbon content.

Fly ash, as collected, is usually basic in reaction. The coarser particles give an acid reaction, while the material passing the No. 400 sieve has a high pH (158).

Grinding, to a fineness of about 10,000 square centimeters per gram, increases the specific gravity to 2.7 (226). Fly ash softens at 1,850° to 2,300° F and fuses at 2,550° to 2,750° F. On calcination, it changes from a gray to a salmon color (53, 243).

HISTORY AND PROBLEM

The fly ash problem developed when the rapid growth in the use of powdered coal in power plants encountered the increasingly restrictive regulations against discharge of smoke, particularly in densely populated areas. The magnitude of the problem may be seen when it is realized that for each ton of powdered coal burned, from 160 to 280 pounds of fly ash are produced. Using the new cyclone burners which utilize crushed instead of powdered coal, as little as 40 to 70 pounds of fly ash are obtained per ton of fuel used. However, only a very small percent of the generating capacity is equipped with these burners at present. With this type of burner, the ash that would otherwise go up the stack as fly ash, is recovered as molten slag, which then presents a problem of disposal in itself, so that in one way or another the ash from the coal presents a disposal problem. As slag, it is good as fill material only, or it might possibly make a pozzolan by grinding (no information regarding this has come to the attention of the writer), but as fly ash it appears to be one of the best pozzolans, a market for which can be developed with a small investment in research and promotion.

The restrictions against the discharge of fly ash through smokestacks led to the development of collecting systems of various types and efficiencies. At first, it was simple to dispose of the relatively small amounts collected, by dumping in nearby locations, but before long, such available sites grew scarcer and more distant while the quantities of fly ash being produced and collected increased at a phenomenal rate. This has been the experience not only in the United States and Canada, but also in other industrial nations utilizing powdered coal, such as Australia, England, France, Germany, and Japan.

In the United States, Weinheimer (158) estimates that the 1953 production of about 6,000,000 tons will increase to nearly 17,000,000 tons by 1963. Homsher's (189) estimate of an eventual production of 17,000,000 tons agrees with the latter figure. In Canada, Durie (238) estimates the present production at about 32,000 tons, and expects it to reach the million-ton mark by about 1975. In Great Britain (163), the 2,000,000 tons estimated as the 1955 production are expected to double by 1960. Jarrige (243) in France estimated the production in 1957 at over 3,000,000 tons.

As the quantities of fly ash being produced increase, the disposal problem becomes more difficult and costly (68). The cheapest form of disposal is dumping near the source. It takes 1¼ to 1½ cubic yards of dumping space for each ton of fly ash (158). Conveniently available dumping areas are therefore fast becoming scarce, and the longer hauls needed to reach available locations increase the disposal cost appreciably. In 1948, dumping costs in the United States varied from 14¼ cents to $1.50 per ton, with an average of 66 cents. By 1954 this average had risen to 95 cents (158), and by now it has probably reached a cost of well over a dollar. In 1954 Weinheimer (158) estimated that the disposal of fly ash loaded the use of pulverized coal with a charge of 7.7 cents per ton, and that when a charge of 22½ cents is made to pulverize coal, other fuels may become more advantageous.

The seriousness of the disposal problem has resulted in concentrated efforts to find uses for fly ash, and turn a liability into an asset (224). Jarrige (243) estimates that the sale of fly ash in France produces revenue equal to the cost of dumping. This is augmented through advantages and savings by its use, and profits in merchandising it, resulting in the creation of wealth equal to the savings for dumping plus the sales price, thus effecting a total creation of wealth equal to four times the cost of disposal. He concludes that no one can afford to neglect such economic possibilities, which turn a loss into an asset four times as large.

USES OF FLY ASH

The efforts to find outlets for this waste product of power production have resulted in developing many uses (2, 5, 12, 14, 23, 24). Many of these uses can utilize very small amounts of fly ash; others, which can account for the use of appreciable quantities, are seasonal in nature, or have encountered strong sales resistance due to already established competitive products for the same purposes (16, 18, 31, 33, 43, 53, 64, 65, 68, 78). The fineness and dust hazard of fly ash, and some of the difficulties in handling it—it has been described as behaving like "liquid smoke"—have developed resistance to its use in many instances (65, 78, 140, 194).

Among the best-known uses are:

Filler in rubber (31, 43, 68, 159)
Filler for paint and putty (68, 78, 102, 152, 159)
Repairing top rot in power poles (27)
As insulation (5, 65, 78)
Raw material for glass (216, 243)
Raw material for bricks (7, 38, 53, 65, 70, 78, 99, 102, 149, 193, 195, 238, 243)
Miscellaneous types of building blocks (2, 5, 6, 12, 14, 34)
Rostone block (2, 5, 6, 12, 14, 68, 78)
Cementing material for miscellaneous aggregates (33)
Filter layer under pavements (243)*
Foundry work (43, 65, 78, 102)
Soil improving agent (43)
Glazed tile (38, 55, 243)
Soil stabilization (43, 65, 78, 151)
Sand-blasting (to replace sand for cleaning turbine blades) (12, 25, 78, 101)
Filler for bituminous concrete (12, 31, 53, 56, 65, 68, 93, 102)
Filler for bituminous products (12, 31, 243)
Lightweight aggregate (34, 36, 53, 75, 161, 214, 216, 238, 243)
Cement manufacture (12, 20, 26, 38, 43, 78, 105, 107, 113, 121, 216)
Concrete construction (various purposes) (3, 12, 16, 31, 45, 79, 81, 102, 216, 226, 243)
Portland cement building block (38, 39, 53, 54, 68, 84, 114, 119, 162)
Concrete pipe (35, 37, 39, 53, 114, 146)
Precast concrete products (5, 159)
Prestressed concrete units
Grouting (49, 53, 246)
Lightweight concrete (43, 88, 104, 118, 149)
Oil well sealing (109)

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*Fly ash can be compacted with an optimum moisture of 25 to 30 percent, and has a relatively high water retention of 40 to 50 percent (243).

SCOPE OF STUDY

This study is concerned primarily with the use of fly ash in concrete construction, and does not deal with many of the miscellaneous uses enumerated above. However, some of the uses related to concrete, which can account for the disposal of large quantities of fly ash, will be touched upon briefly insofar as they have come to the attention of the writer in his study of the concrete problem.

Of the potential uses that could utilize appreciable quantities of fly ash, soil stabilization, special blocks (not using portland cement), and brick manufacture, are being intentionally excluded from this study as being definitely outside the concrete field.

Bituminous Concrete and Bituminous Products

In bituminous construction, fly ash is used as a filler or as a lightweight aggregate. The latter use has not been developed in the Unived States because lightweight aggregate from fly ash is not being produced commercially, so that this discussion is restricted to the use of fly ash as a filler in bituminous work. The earliest work on this utilization was done by the Cleveland Electric Illuminating Company and the Detroit Edison Company, starting in 1932 (12, 31, 43, 56, 78, 94, 95, 158, 209). Detroit Edison Company had this application well under way by 1939, and has since successfully disposed of relatively large amounts of fly ash for this purpose.

In 1952, the Bureau of Public Roads reported tests (93) which indicated that fly ash makes a superior filler for use in asphaltic concrete. Fly ash is hydrophobic and therefore reduces the tendency towards stripping, has good void filling capacity, and provides good stability (56).

In some areas, interests with large investments in plants for making limestone dust for filler have succeeded in thwarting the use of fly ash, even though fly ash delivered to the asphalt plant may cost half what limestone dust does.

Fly ash has been used successfully in bituminous products made in industrial plants (12, 31, 243). This use can account for relatively small quantities of fly ash but is normally a year-round market, as contrasted with the larger construction field, which is of seasonal nature.

Lightweight Aggregate

Many attempts to utilize fly ash for the production of lightweight aggregate have been made, the most successful of which have been in Europe, particularly in England (34, 36, 53, 75, 161, 164, 167, 181, 190, 193, 214, 216, 238, 243). Some activity is under way in the United States, and it is possible that some commercial plants will be producing it competitively before long.

The interest in lightweight aggregate stems from the fact that the demand for this commodity has been increasing at a very rapid rate. The outlook is that the rate of increase will continue to accelerate for many years to come. Advantages for the use of lightweight concrete are not only its lightness which results in structures with lighter foundations and structural members, but also its concomitant sound and heat insulating properties, and resistance to fire.

From the fly ash disposal standpoint, the lightweight aggregate field meets the ideals for a good market as outlined by Weinheimer (158).

SINTERING PROCESS

The most comprehensive work in the field of making lightweight aggregate from fly ash has been carried on in England, where various processes and types of equipment have been tried. The most promising process involves forming the fly ash powder into pellets, then heating these to incipient fusion temperature, thus sintering them to a hard, strong product having a density of 37 to 52 pounds per cubic foot (217)—a weight of the same general order of magnitude as that of many other lightweight aggregates.

Sintering may be defined as the passing of air through a layer of material that will support combustion and thus consolidating the particles by thermal bonding (196, 217). Because of the fine texture of fly ash, it is necessary to pelletize it prior to sintering in order to be able to force air through it.

Normally, very little or no binder is used in the pelletizing process, and no fuel is added as the carbon particles in the fly ash will usually support combustion to produce the required temperatures. As little as 2½ percent carbon in the fly ash will suffice under proper circumstances (238). Fuel may be added in the form of powdered coal if necessary, and a binder is used in some cases to hold the fly ash particles together.

EUROPEAN WORK

A full-scale plant has been built in England (190, 196, 207, 238), for an ultimate capacity of 300 tons per day utilizing two vertical kilns. The aggregate is marketed in three size classifications and is known as "Terlite."

Comparison of this aggregate with three other commercially available lightweight aggregates indicates that with the same cement content and fine and coarse aggregate proportions, Terlite gives the strongest mix, and is the third heaviest. It is estimated that Terlite mixes will require about 1½ sacks less cement per cubic yard of lightweight concrete than other mixes for the same strength (238).

Jarrige (France) (243) describes the different methods of pelletizing, and sintering in vertical furnaces, rotary kilns, and by the use of traveling grates.

Gumz (Germany) (214) describes a sintering belt and shaft kiln used to sinter fly ash for aggregate.

CANADIAN EXPERIMENTS

Ontario Research Foundation of Canada, using Canadian fly ash, conducted experiments in which fly ash was pelletized and fired in a rotary kiln. Because the vitrification range of fly ash seemed to be short, this process was sensitive to over- or underburning. The work has progressed sufficiently to indicate the feasibility of producing lower weight aggregate than that from expanded shale. However, the concrete-making properties of this aggregate are not yet shown (238).

UNITED STATES DEVELOPMENT

In the United States, Leftwich reported mixing fly ash with slag, sintering, then crushing and sieving to proper sizes. The resultant aggregate was used for making building blocks (34).

Another lightweight aggregate known as "Sinter-Lite" was reported being produced in the Bronx, New York, in 1947 (36), by sintering fly ash at 2,400° F, then crushing and grading it. Fly ash was obtained from the Consolidated Edison Company, and contained 6 to 20 percent carbon. The product weighed 34 to 56 pounds per cubic foot, and the production was about 125 cubic yards per 8-hour day. This was used in making building blocks—4,800 units per day.

Research on lightweight aggregate from fly ash was also conducted in 1950 at Alfred University (75). It indicated the feasibility of pelletizing and heating the fly ash in a rotary furnace at 2,200° F, which resulted in lightweight aggregate weighing 38 pounds per cubic foot. Another process, in which fly ash was sintered and then crushed, produced aggregate weighing 40 to 50 pounds per cubic foot.

Garloni (212) obtained a patent on pelletizing and then expanding pellets into lightweight aggregate.

A pilot plant has been developed by Koppers Company in Pittsburgh. The plant uses a traveling grate, and in the process a small amount of binder is mixed with the fly ash prior to pelletizing. In this process a carbon content of 3½ percent will support sintering. Lower carbon fly ash needs additional fuel to support combustion. The work at this experimental plant indicates that 1½ to 3 tons of aggregate per square foot of grate, per day, can be produced. The material weighs 37 to 52 pounds per cubic foot. Cost is estimated at $1.23 per cubic yard of finished fly ash aggregate, exclusive of the cost of the fly ash. This compares favorably with the price of $3.15 to $5.15

per cubic yard for lightweight aggregate in New York City (217).

So far, the vertical furnace seems to be favored in England, the rotary-type kiln has been used in the experimental work in Canada, and the traveling grate seems to be the preferred equipment in the United States. The traveling grate appears to provide more flexible control and continuous observation of the process, but it is claimed to require more fuel, and because of the larger number of moving parts it needs more maintenance (238).

Portland Cement Concrete

The use of fly ash in portland cement concrete and in concrete products has received more attention than all other applications, even though lightweight aggregate has a larger volume potential, per cubic yard of concrete, from the disposal standpoint. The reason for this is that fly ash imparts many desirable properties to concrete, such as increased workability (3, 13, 19, 31, 46, 60, 61), reduced segregation and bleeding (3, 60, 61, 79, 201), reduced mixer and mold wear (masonry units), increased green strength (masonry units), higher ultimate strength (3, 19, 45, 60, 61, 97, 139, 188, 194, 200, 238, 260), enhanced sulfate resistance (3, 21, 60, 79, 187, 245, 260), reduced alkali-aggregate reaction, and lower cost.

In most instances the lowered cost of the concrete makes the use of fly ash advantageous, even without consideration of the other advantages. Some of these advantages are the result of the pozzolanic action of fly ash.

POZZOLANS

Long ago, it was observed that some siliceous materials when mixed with lime produced cementing compounds possessed hydraulic properties. Such a material was a consolidated volcanic ash found near Pozzuoli, Italy (50, 52, 60). As a result, the term "pozzuolana" became generally applied to similar deposits found all over southern Europe. From this has evolved the modern term "pozzolan."

Pozzolans may be defined as siliceous or siliceous and aluminous materials (low in lime content) which possess in themselves little or no cementitious properties, but which in finely divided form will, in the presence of moisture, react chemically with calcium hydroxide, at ordinary temperatures, to form insoluble compounds possessing cementitious properties (16, 59, 60, 79, 111, 146, 177, 191, 194, 205, 211, 227, 228, 237, 258). Fly ashes high in lime do not possess pozzolanic properties (211).

Lime and silica (in the form of sand) combine in a wet environment at 355° F and under a pressure of about 150 pounds per square inch, to form a calcium silicate compound. Lime does not react with ordinary sand at normal temperatures and atmospheric pressure, but it does with certain finely divided sands of volcanic origin known as pozzolans (243).

The hydration of portland cement is accompanied by the liberation of lime (calcium hydroxide) (126, 183), which carbonates progressively, but which can be leached out, leaving a relatively porous concrete, or it can combine with the sulfates in aggressive waters causing expansion which disrupts the concrete.

Pozzolans incorporated in portland cement concrete fix the lime liberated by hydration, increasing the watertightness of the concrete and its resistance to sulfate attack (3, 16, 22, 41, 48, 82, 226, 257).

Many pozzolans with as little as 40 percent silica content exhibit satisfactory performance (60). Those regarded as the better pozzolans contain from 5 to 10 percent alkalies. Some contain as much as 30 percent alumina, and as much as 20 percent iron oxide. The presence of a small percentage of alkalies is more likely to be favorable than unfavorable (146, 211), and those containing an appreciable percentage of alumina and iron oxide are better than those that contain a very high percentage of silica (211).

A variety of tests have been proposed for determining the pozzolanic activity of a material (72, 149, 160, 182, 233, 236, 242, 244, 245, 258). Pozzolans are classified as natural pozzolans and artificial pozzolans (237). Natural pozzolans are materials that are found in nature which possess pozzolanic properties, or which can be converted easily into pozzolans by processing (111). Artificial pozzolans are those derived from industrial waste products (60).

The most important artificial pozzolan is fly ash (61, 79, 111). In many ways, it is produced under conditions simulating very closely the natural conditions under which the volcanic ashes of Pozzuoli, Italy, were produced.

Pozzolans combined or interground with portland cement have definite advantages in concrete (3, 8, 18, 41, 46, 47, 48, 58, 69, 100, 112, 211, 243), among which are:

1. Reduced water demand, in case of fly ash.
2. Improved workability.
3. Reduced segregation.
4. Reduced bleeding.
5. Lower heat of hydration and resulting decreased volume change.
6. Reduced drying shrinkage.
7. Increased extensibility and plastic flow at early ages.
8. Improved formed surface finishes.
9. Increased ultimate compressive strength.
10. Increased ultimate tensile strength.
11. Reduced permeability and leaching.
12. Reduced alkali-aggregate reaction in most instances.
13. Improved freezing and thawing durability when moist cured prior to freezing exposure.
14. Improved sulfate resistance.
15. Reduced cost.

As a pozzolan, fly ash has many advantages over other materials:

1. It comes already in a finely divided form so essential to pozzolanic action, whereas many of the natural pozzolans have to be ground (177).
2. It is already in the proper chemical state, whereas many natural pozzolans have to be calcined at high temperatures to bring out their activity (177).
3. It is a waste product to be disposed of, and therefore already available, whereas natural pozzolans have to be mined or dug out of deposits.
4. It is produced in the centers of population where the largest volumes of concrete are used.
5. Statistical significance of variables in fly ash can be determined more readily than for natural pozzolans, the variables of which are almost infinite (111).

CHRONOLOGY OF USE OF FLY ASH IN CONCRETE

Early Work (1932-1947)

The earliest work on record conducted to find uses for fly ash was carried on by the Cleveland Electric Illuminating Company and the Detroit Edison Company, and was reported in 1932. Insofar as portland cement concrete is concerned, this work touched on its possibilities as a raw material for cement, and as a natural cement (152).

The earliest over-all comprehensive work on the use of fly ash in concrete was reported by Davis and his associates of the University of California (3) in 1937, and in later reports (13, 19, 60, 61, 79, 146). Davis found in general that:

1. Fly ash varies in detailed chemical composition, the principal difference as far as effect on concrete being its carbon content.
2. Fly ash is usually finer than cement, and the particles are mostly spherical in shape.
3. Fly ash exhibits pozzolanic properties, as judged by its ability to combine with lime.
4. Fly ash of low carbon and high fineness can be used as a 30 percent replacement of cement in concrete that is standard moist cured.
5. Fly ash under mass curing conditions may be used in as high as 50 percent replacement.
6. Most favorable results are obtained by using fly ash with cement of normal or

high fineness and of normal or high lime content.

7. Mixing fly ash with cement gives as good results as intergrinding with cement, except that the latter results in higher early strength concrete.
8. Fly ash retards the setting time, but this remains within usual specification limits.
9. Water-reducing agents are more effective in concrete with fly ash, than without.
10. Fly ash can be used in quantities exceeding cement replacement, and such excess can then be considered as replacing the sand fines, thus permitting a reduction in the amount of sand.
11. Suitability of fly ash cement mixtures can be evaluated by standard physical tests for cement; that is, time of set, autoclave expansion, and tensile and compressive strengths of mortar.

Davis further found that the properties of the concrete in which fly ash of relatively low carbon content and high fineness is used, as compared to the same concrete without fly ash, are affected as follows:

1. Water requirement is about the same or lower. The lower the carbon content and the higher the fineness, other things being equal, the lower the water demand, and the latter is lower than for any other pozzolan.
2. Improved workability.
3. Reduced tendency to segregation and bleeding.
4. For a 30 percent replacement and standard curing, the early strength is lower than for plain concrete, but becomes higher after 3 months.
5. Under mass curing conditions, the strength of fly ash concrete is higher than for plain concrete, even at 28 days.
6. By intergrinding 20 percent fly ash with normal fineness cement, using the same total grinding energy, substantially the same 3-day strength as the corresponding Type III cement may be obtained.
7. Increased ultimate compressive strength is not affected by richness of mix.
8. Modulus of elasticity is lower at early ages and higher at later ages, but not significantly.
9. Shrinkage in most instances is reduced.
10. Autoclave expansion is reduced.
11. Resistance to freezing and thawing (5 months' moist curing prior to exposure) is increased.
12. Resistance to sulfates is increased.
13. Heat of hydration is reduced.
14. Plastic flow at early ages is greater, and lower at later ages, with total about same.
15. Permeability and leaching are reduced.

James (5) in 1937 reported on the use of fly ash in cinder blocks and in the patented "Cottrell" (Rostone) block (2). He found that he could obtain cinder blocks of 3,000-psi strength at 28 days using an equal mixture of fly ash and portland cement with crushed cinders. The Cottrell block, which is 90 percent fly ash, was found to have good insulating and fire-resistant properties.

By 1938 and 1939, Thorson and Nelles (12) and Ramseyer (16) were concerned with the problem of disposal and the various possible uses and advantages of fly ash. Many uses were reported and evaluated by these investigators. A great many were eliminated, and the use of fly ash in asphalt as filler, in building blocks, and in concrete appeared to them to be most promising. Ramseyer discussed the disposal problem, and the use of fly ash as a pozzolan, and cited the many advantages which had been found by Davis.

The earliest use of fly ash in concrete that has come to the attention of the writer, is the seawall at State Line Plant in Chicago, placed about 1936. An examination by the writer in March 1958, or 22 years later, shows it to be in reasonably good condition. Lake Michigan water is constantly in contact with it. No information is available regarding its construction. Whether any serious freezing and thawing problem exists is not known, as the condenser cooling water discharged from the power plant may keep the lake water in contact with the wall above freezing. It is still serving its purpose, and appears to be in reasonably good condition. Because of the many unknowns involved, it is felt that no positive conclusion can be reached regarding this structure.

Another early application in concrete was in the pavement for the Northside Sewage Treatment Plant in Chicago, Illinois, in 1938—a WPA project. Sections of pavement with a wide range of variables were installed in this project. Fly ash was used in 18 to 50 percent of the total cementitious materials in the various sections, and the tendency for the concrete to become "gummy" where the fly ash exceeded 30 percent by volume was reported. In 1953, McClenahan (124) evaluated the pavement and found that the skin coat had disappeared, exposing the coarse aggregate (salts have been used for de-icing). Raveling was observed only in low spots where water collects and freezes. Map-cracking was evident in only two sections where no fly ash was used.

The writer examined this pavement in March 1958, or approximately 20 years after it was built. The same scaling described by McClenahan, the raveling and map-cracking were observed and were possibly in a more advanced state. Inasmuch as the pavement was placed and finished by hand, before the days of air-entrainment, it is probable that placing conditions were rather on the wet side, and that a lot of wet mortar was floated to the surface in the finishing process. Considering these factors, its age, the fact that salts are used constantly in winter for de-icing, and that it is still in service, it would seem to have fulfilled its purpose. However, there does not seem to be any consistent pattern that would lead to any reliable conclusions as to the favorable or unfavorable effect of fly ash in this instance, particularly since it had no air-entrainment and has been salted consistently in cold weather.

In 1940 Nelles and Sellke (18) enumerated the properties of fly ash and its advantages in concrete as:

1. Noncombustible particles similar to vitrified clay.
2. Combustible particles—essentially coke.
3. The higher the carbon content, the coarser the fly ash.
4. Fly ash has unit weight of about 46 pounds per cubic foot by ASTM Designation C 29.
5. Improves grading or faulty proportioning of aggregate.
6. Improves workability.
7. Increases plasticity and density.
8. Reduces segregation and bleeding.
9. Provides pozzolanic action.
10. With 20 percent substitution by weight, it results in increased strength after 28 days.
11. Increasing fly ash in excess of substitution produces strength gains at earlier ages.
12. Reduces permeability.
13. Provides superior concrete at lower cost.

The same year Elmer (17) gave details of proper airtight handling systems to assure the collection of higher quality fly ash.

In 1941, in Europe, Kronsbein (20) tested 14 fly ashes and discussed their use in concrete, and as raw materials in cement manufacture. He reached the conclusion that where fly ash is used in concrete and the mix adjusted by reducing the cement content by an amount equal to the fly ash, the concrete can be only used in structural members in which early strength is not important, because of the relatively low early strength of fly ash concrete.

Nelles (22), also in 1941, called attention to the superior resistance of concrete containing fly ash when used in exposure to sulfur water and gave results of 12-year exposures.

In 1942 the Bureau of Reclamation used fly ash in the repair of the Arizona Spillway Tunnel at Hoover Dam (237).

The Germans (23, 24, 26), also in 1942 and in 1943, tried various successful applications of fly ash in concrete—mostly in the less critical locations of structures.

Frederick (29), in 1944, reported its use as a 25 percent replacement for sand in lean concrete mixtures. He found that it produced harder surfaces and denser concrete than plain concrete.

The same year, the report of the American Concrete Institute Committee on Admixtures (30) suggested its use as a pozzolan in amounts of 20 to 30 percent, and as a workability agent in amounts of about 20 percent.

About the same time, Weinheimer (31) gave details of physical and chemical properties of fly ash, and reported on the various uses, and handling problems.

By 1946 Leverett (35) reported on its use in concrete pipe (25 percent) by the Continental Concrete Pipe Company, and the Illinois-Wisconsin Concrete Pipe Company. It resulted in smoother pipe and in a 50 percent higher strength than ASTM requirements, when steam cured at 100° F for 48 hours.

Bessey (38) in England, in 1947, expressed pessimism on the use of fly ash. Although admitting its technical feasibility, he doubted the economics of its use, and described the many unknowns to be faced.

Rapid Expansion (1948-1952)

The big break came in 1948, when the U.S. Bureau of Reclamation (45, 52, 57, 76, 83, 91, 112, 128, 136, 237) decided to use fly ash in the concrete of Hungry Horse Dam. This was the fourth largest dam in the world at the time it was built and was estimated to need 261,000,000 pounds of fly ash and 342,000,000 pounds of cement (57). Extensive testing and research were conducted before the decision was made. The findings confirmed, for the most part, the conclusions which had been reached by Davis and his associates, and may be summarized:

1. Reduced portland cement requirements.
2. Reduced cost due to difference in prices of fly ash and portland cement.
3. For lean mixes fly ash reduces water requirements, but for rich mixes, it does not affect it. On an equal weight replacement basis, it is unique among pozzolans in that it reduces water requirement.
4. Increased workability of concrete.
5. Reduced segregation and bleeding.
6. Greater extensibility.
7. Greater impermeability.
8. The 90-day mortar cube strength was 92 percent and 122 percent of plain portland cement control, for standard and mass curing, respectively, with 35 percent replacement by absolute volume (25 percent by weight).
9. Reduction of expansion in expansion bars for alkali-aggregate expansion reaction, for 30 percent replacement was 59 percent at 14 days, and 81 percent at 90 days.
10. Strength gain of concrete containing 30 percent fly ash is not as rapid as plain concrete, but continues for a longer period. Both reach the same strength at about 1 year.
11. Fly ash increases modulus of elasticity for same compressive strength.
12. Fly ash generates 40 to 50 percent as much heat of hydration as same weight of cement.
13. Moist-cured fly ash specimens show slightly more expansion, and lower drying shrinkage.
14. Fly ash retards autogenous shrinkage at early ages, increases shrinkage of rich mixes at later ages, but compares favorably in amount of shrinkage with lean mixes without fly ash.
15. Fly ash concrete has high thermal coefficient of expansion, but cement brand may be a more important factor in this property.
16. Good freezing and thawing resistance is obtained with fly ash concrete (40 percent replacement), moist cured, 28 days, or 180 days, or 14 days, and then dried at 50 percent relative humidity, prior to freezing cycle exposure.
17. Fly ash reduces permeability of concrete.
18. Early strength is reduced in proportion to amount of fly ash added, but catches

up at age of 1 year, and ultimate strength is higher.

19. Reduction of alkali-aggregate reaction is lower for fly ash than for opaline silica.
20. Optimum replacement, with low carbon and high fineness fly ash, is 30 to 40 percent.
21. Fly ash concrete has considerable variation in entrained air content.
22. Fly ash from different sources requires different amounts of air-entraining agent.

The use of fly ash on this project resulted in a saving of $1,675,000, and together with air-entrainment is credited with permitting the completion of the dam more than 1 year ahead of schedule, while resulting in concrete having 5 to 10 percent higher strength at age of 2 years (237).

The following summer (1949), the McPherson Test Road in Kansas (74, 108, 174) was constructed, in an effort to find a solution to the problems that develop in concrete construction in the Plains area when local sand-gravel aggregate is used. This local aggregate, characterized by having only 5 to 15 percent retained on No. 4 sieve, and usually all smaller than ½ inch, causes excessive expansion in concrete, which results in bad map-cracking. Preliminary laboratory tests had indicated that certain pozzolans, among them fly ash, might be useful in inhibiting part of the expansion due to this cement-aggregate reaction—a reaction that cannot be entirely ascribed to the characteristic alkali-aggregate reaction. The Test Road included sections with different mixes to test the various possibilities that had been suggested as remedies to this detrimental expansion. It was found that:

1. Fly ash permitted retaining same water-cement ratio as control mixes, whereas other pozzolans required more water.
2. Fly ash with air-entrainment permitted a reduction in the cement content of 0.15 barrel per cubic yard of concrete.
3. Placing and finishing were easiest with fly ash mixes due to retarded set, whereas other sections had to be shortened in warm weather, and sprayed with water to facilitate finishing.
4. Fly ash reduced air content, and required more air-entraining agent to maintain required air content.
5. Workability was improved and placing was very simple compared to other pozzolan mixes.
6. Mix was not sticky and gummy like other pozzolan mixes.

An evaluation of this Test Road after 5 years of service (174) indicated:

1. Brand of cement seems to have more influence on inhibiting map-cracking than pozzolans.
2. Only fly ash among pozzolans shows less map-cracking than control mixes.
3. Deterioration is present in air-entrained concrete to a greater degree than in non-air-entrained concrete.
4. Durability of all concrete mixes against freezing and thawing improved by air-entrainment to larger extent than in fly ash mixes.
5. None of the pozzolans have been as effective in inhibiting map-cracking as limestone "sweetening" (additions of crushed coarse limestone aggregate), but fly ash is best of three pozzolans that were used.
6. Measured expansion in field is slight.
7. Field observations inconsistent with laboratory predictions, and evaluations appear contradictory depending on method used.
8. Possibility that a combination of limestone sweetening and fly ash, which combination was not tried on this road, may offer a better solution than anything tried so far.

The writer examined this project in March 1957, or 8 years after it was constructed. Experience has indicated that the age between 8 and 10 years is the most critical period with regard to the appearance of map-cracking due to this type of cement-aggregate reaction. Distress in the form of map-cracking was evident in most slabs. Except for one section, over-all expansion by closing of joints was not observed. Structural and subgrade failures, as well as faulting and pumping, are in evidence. An interesting, but unexplained, observation is the characteristic increase in frequency and intensity of map-cracking from the south towards the north in any given section. The test beams placed at the edge of the right-of-way do not show as much distress as the corresponding pavement. The next few years may differentiate between the behavior of the various sections. However, at present no conclusive pattern of behavior could be determined. All mixes showed map-cracking, the least being in the limestone sweetening sections. Of the various pozzolans, the fly ash appears to have a slightly better performance than the others, and definitely better than the control. Peyton's (174) suggestion (No. 8 above) regarding the possibility of combining limestone sweetening and fly ash, may be worth serious consideration.

This same year, in September 1949, Larson (51, 123, 138, 150) used fly ash in an experimental pavement in Wisconsin. The work consisted of 3.3 miles of pavement on U.S. 10, east of State No. 13. Plain mixes with air-entraining cement, mixes with 21 percent fly ash replacement without air adjustment (thus giving reduced air content), and mixes with fly ash replacement and air-entraining agent added to restore air content to original level, were used in various sections. The use of the last type of mix predominated.

Construction started September 20, and continued till about the middle of November. No reinforcing mesh was used, and curing was by paper. There was some rain and light snow at times during the construction period. Temperature of the concrete as placed was 60° to 70° F. It is reported that there was no bleeding noticeable for the fly ash mix with the added air-entraining agent. Cores taken after 3 years showed no adverse weathering effects on any of the sections.

This road was examined by the writer in June 1958, or 9 years after it was constructed. No differences in the behavior among the three types of concrete could be observed. The pavement appeared in good condition, and there was no evidence of any problem or failure due to the concrete. The concrete was constructed with contraction joints at 20-foot spacing except the middle section (over a mile long), which was all in one piece. This section had many cracks, which was to be expected. At two intersections, where salts are used profusely in winter and where shoulder gravel is ground into the surface by turning cars, scaling was in evidence. No salts are used between intersections.

Another landmark this year (1949) was the beginning of construction by the Bureau of Reclamation of Canyon Ferry Dam, in which fly ash was used in the concrete (110, 112, 132, 155).

In 1950, the Australians, following up on the work of Davis and the Bureau of Reclamation, reported (73) results of successful tests with their East Perth fly ash. Comparing their results with those obtained on American fly ash, they found their material of very good quality for use in concrete. It is high in silica and iron, low in alumina, sulfur and carbon, and very low in calcium oxide. They concluded that:

1. East Perth fly ash has pozzolanic properties.
2. After 6 months the strength of the fly ash concrete is about the same as that of control.
3. Replacement by weight up to 25 percent would be safe.
4. East Perth fly ash is not detrimental to concrete and compares favorably with fly ash already in extensive use in the United States.

About the same time (August and September 1950), because of a cement-aggregate reaction similar to that found in Kansas, Nebraska built an experimental pavement (Fremont to Arlington) utilizing various mixes including fly ash (117). The following year (September to November 1951), another section using fly ash mixes and some admixtures was constructed in Nebraska (Laurel to Belden), under standard construction procedures (87). The preliminary laboratory work for the experimental pavement and the observations during its construction resulted in the following conclusions regarding effect of fly ash (this applies only to the special mixes, which are basically fly ash, cement, sand-gravel aggregate—lacking the normal proportions of coarse aggregate):

1. Reduces expansion with Scholer Exposure No. 2, and improves durability in Nebraska freezing and thawing test.
2. Expansion bars stored at 100° F, made with 30 percent fly ash replacement, showed complete inhibition of expansion.
3. During construction, fineness of fly ash presented handling problems, but not insurmountable.
4. Requires more air-entraining agent, and this seems to be directly proportional to carbon content.
5. Lowers water requirement.
6. Increases workability.
7. Very little bleeding developed.
8. In hot, dry, windy weather, some rubberiness and difficulty in finishing were experienced with the high fly ash replacements, and high air-entrainment.
9. Cores taken from pavement had lower absorption for the fly ash mixes than for the control mixes.
10. Lowers compressive and beam strengths at early ages, but increases eventual strengths.
11. Reduces excessive expansion effect of cement-aggregate reaction.

The regular pavement section built in 1951 used 25 percent replacement in 85 to 90 percent of the area, and plain concrete in the balance. All concrete was air-entrained. No wire mesh was used, and joints were spaced 16 feet 4 inches apart. A maximum limit of 3 percent carbon and a pozzolanic activity test were required by the specifications.

Both projects were examined by the writer in August of 1958, or 8 and 7 years, respectively, after the construction of the experimental and the regular pavements.

The performance does not seem to be as jumbled as in the McPherson Test Road in Kansas. On the experimental pavement, frequent belt marks and tears are in evidence on most sections, possibly an indication of the dry condition of the surface at the time of belting, probably due to hot, windy weather. There is no doubt that the limestone sweetening appears to be the best from the standpoint of absence of map-cracking and shrinkage cracks, although the latter seem to vary with the brand of cement used. The fly ash appears to be next to limestone sweetening in effectiveness, when judged by these criteria.

Considering the fact that it replaces cement at half the latter's price, it would definitely result in a lower cost mixture than the limestone sweetening. It is too early to tell whether the fly ash would perform sufficiently well by itself, or whether a mixture with the limestone as has been suggested for Kansas would be desirable. The next 2 years will be the critical period on this project, and it bears close observation.

The second project built under standard construction procedures shows some wheel track wear concentration in a few places, and occasional shrinkage cracks in various sections, but otherwise no evidence of any distress attributable to the concrete is apparent. Some difficulties must have been experienced in the finishing during the hot, windy weather, as belt marks and tears are in evidence, possibly an indication of the sticky and gummy condition of the concrete surface at the time of belting. This may be minimized by adjusting construction procedures and operations, after once the workmen become familiar with the manner in which fly ash concrete should be handled. In general, this project shows excellent performance for fly ash concrete in the sand-gravel aggregate problem area.

An indication of the world-wide problem of fly ash disposal or utilization is the publication of results of work done by the Hydro-Electric Power Commission of Ontario, at about the same time, in 1950, as the Australian reports (59, 97). The laboratory and field tests substantiated in essence the major findings of Davis and the Bureau of Reclamation in the United States.

Using 30 percent by weight substitution in a section of the dam for the Otto Holden Generating Station, fly ash was found to increase workability, and to reduce the water requirement 7 percent from that in a similar adjacent control section. The fly ash mix developed lower heat of hydration, and as a result lower shrinkage. The strength was low up to 15 days, but after that exceeded the control mix. Cores substantiated the cylinder strengths, with the latter cured in a well in the dam concrete to simulate mass curing.

Another experimental pavement using fly ash concrete was installed in 1950 in Baltimore, Maryland (94, 95, 96, 98, 235). Both fly ash and plain concrete sections were placed side by side. In this pavement, located on Cooks Lane near Alson Drive, one sack of air-entraining cement was replaced by fly ash. This reduced the normal 3½ percent air-entrainment to 2½ percent. The fly ash had 5 percent loss on ignition, and a fineness of 3,010 square centimeters per gram. The compressive strength was lower than the control at early ages, and equaled it at age of about 90 days, then started to exceed it, and cores taken after 7½ years shows the fly ash concrete to have a strength of 6,355 psi against the control concrete strength of 5,605 psi. There is very little difference in wearing qualities between the two concretes, and the test section is heavily traveled, with a bus routed over it, and is salted in winter.

The writer visited this test road in 1957, and again in 1959. The pavement is on a sloping hill and the appearance is excellent. Occasional slab corners are beginning to break or ravel, but this is true of both the fly ash and control concrete. This pavement is thus standing up nicely after about 9 years of service.

This same year (1950) research on lightweight aggregate from fly ash, and the development of pelletizing prior to sintering were reported by Alfred University (75). Two laboratory sintering methods were tried successfully.

A big step forward was taken by the French in 1951 (113, 121, 149, 211, 226, 240, 242, 243), when they came out commercially with two cements containing fly ash. These cements develop early strength gains essentially similar to standard French portland cements, while the ultimate strengths surpass the ultimate strength of French super cement. These cements are interground combinations of fly ash, blast furnace slag, and portland cement clinker. A French patent was issued in 1953.

It is claimed that although either binary combination—fly ash-portland cement clinker or blast furnace slag-portland cement clinker—results in a cement that has low early strength, the intergrinding of all three constituents (fly ash, slag, portland cement clinker) in the proper proportions results in a cement of normal early strength and higher ultimate strength than standard portland cement, with the added advantages of pozzolanic properties. Later, in 1956, the French developed a cement with 20 percent finely interground fly ash, which falls within the regular portland cement specification. This cement gives early strength gains essentially the same as plain portland cement, and provides the advantages of pozzolanic cements, although not to as high a degree as the cements containing both fly ash and blast furnace slag. It is claimed that the grinding of the fly ash particles exposes a larger active surface area, which increases early pozzolanic action, thus resulting in the higher early strengths. These cements open the wide field of small concrete construction to fly ash—a field hitherto untapped because of the difficulty of handling and batching fly ash as a separate ingredient, and because of the low early strengths that delay form stripping on structural work.

In 1952, research on fly ash was reported from the Norway Institute of Technology (92). The work covered the use of fly ash as an admixture and as a replacement for cement up to 30 percent. Compressive strength, freezing and thawing, and resistance to sodium sulfate were determined for various mixes. The author defines the efficiency of a cement as being the compressive strength divided by the cement content per unit volume of concrete. This efficiency was found to increase with the percentage of fly ash replacement. Even the efficiency of the cementitious materials (cement plus fly ash), increased up to replacements of 10 to 15 percent. This increase in efficiency was particularly pronounced for lean mixes. Resistance to freezing and thawing, as well as resistance to sulfate action, was found to increase up to replacements of 10 to 15 percent.

The Bureau of Mines felt in 1952 that fly ash had become of sufficient interest to warrant the publication of an annotated bibliography (102).

Scholer (108), also in 1952, found that fly ash used as 20 to 30 percent replacement was sufficient to inhibit the cement-aggregate reaction that develops when the local sand-gravel aggregate is used in the Kansas-Nebraska area. This conclusion was based on a laboratory wetting and drying test that had been found to correlate with outdoor exposure.

Also in 1952, the Bureau of Reclamation started work on Palisades Dam (130), where fly ash was used in the tunnel concrete, and reported results of comprehensive studies of cement-pozzolan reactions, and how fly ash fits into the over-all pozzolan picture, and concluded that fly ash variables were more easily evaluated statistically than variations in natural pozzolans. Another study by the Bureau of Reclamation (110), made in connection with the investigation of materials for Canyon Ferry concrete, measured the effect of fly ash and pumicite on the freezing and thawing durability of concrete. Compared to the control mixes, it was found that:

1. Fly ash in 15 percent replacement increased the resistance of non-air-entrained moist-cured concrete to freezing and thawing, and this increase was more marked with the longer moist curing periods. Higher replacements decreased this resistance.
2. In air-entrained concrete moist cured for 6 months, 30 percent fly ash replacement increased the resistance to freezing and thawing.
3. Moist curing (7 and 14 days), followed by laboratory or outdoor drying, reduced the durability of fly ash concrete in direct proportion to the amount of replacement used.
4. Shrinkage cracks, or low strength at time of starting of freezing cycle, may be the reasons for the lowered resistance after drying.

About this time, the Halliburton Company (109) developed a mixture for oil well cementing using 50 percent fly ash. The advantages claimed are:

1. Lowered heat of hydration and therefore reduced volume change.
2. Improved tensile and compressive strengths.
3. Improved resistance to sulfates.
4. Reduced leaching.
5. Reduced cracking.
6. Lower pressures needed for sealing.
7. Lower cost.

Continuing Development (1953-1959)

Reports of these various early experiences with fly ash concrete were circulated and commented on all over the world, and stimulated further work in this field wherever industrial developments produced large quantities of fly ash. Thus, the various problems encountered in the use of fly ash in concrete were receiving world-wide attention.

In 1953, the Chicago Conference Committee on Concrete Tests made public its test results which showed the advantages of fly ash in concrete exposed to sewage, and other concrete in the Chicago area (120, 166). The resulting general recommendations were:

1. To use air-entrainment for highway work, and to take advantage of saving by use of fly ash in the mix when no urgency for early opening to traffic exists.
2. For heavy concrete sections, it may be advantageous to utilize the reduction of heat of hydration resulting from fly ash substitution with Type I cement, and in extreme cases even with Type II cement.
3. For sewer work use Type II cement or Type I with fly ash, but not Type I alone.
4. All concrete should contain 3 to 5 percent air.
5. Winter curing should provide 70° F for 3 days in the case of straight cements, or 5 days at 70° F for fly ash blends, after which the concrete should be protected from freezing until it has developed ⅔ of its specified strength.

At about the same time, the Consolidated Edison Company (126) was able to introduce provisions into the New York City Building Code permitting the use of fly ash in concrete.

The same year the Bureau of Reclamation issued several reports on investigations for various projects, using fly ash as cement replacement (128, 129, 130, 131, 132, 133, 134, 135, 136). The results of these investigations confirmed in general the previous findings. The additional findings, with the specific materials used in the tests, and with the comparatively lean mixes used in dam construction, were:

1. Resistance to cavitation is decreased, except for 4-sack concrete mixes, mass cured for 90 days, and with a maximum of 15 percent fly ash, which had better resistance than the control. In spite of this decrease, the values were rated as good for mass concrete.
2. Abrasion resistance is reduced for all conditions tested (3- and 4-sack mixes), mass cured for 28 and 90 days. The lowered values obtained were still rated as good for mass concrete.
3. Fly ash reduced the effectiveness of calcium chloride at 50° and 73° F using Types II and V cement mixes, but there still was a net gain in strength at the lower temperature as compared to control.
4. Fly ash concrete mass cured for 1 year had a high degree of correlation with fog-cured concrete at 28 days.
5. Fly ash in concrete mixes increased thermal conductivity and diffusivity.
6. Fly ash was more effective in leaner mixes.

In the same year (1953) it was reported that fly ash was used in the concrete of six dams built by the Niagara-Mohawk Power Company (115), and in Liberty Dam (near Baltimore) (116).

In 1954, the use of fly ash in concrete mixes in excess of the amount of cement taken out of the mix (which produces early strength gains comparable to control mixes with cement alone) began to gain ground. This came as a result of the publication in 1953 of test results by Washa and Withey (137) confirming this idea, which had been proposed earlier by several investigators (18, 29, 114).

British interest became evident in 1954, through an investigation for the British Electricity Authority to verify American experiences (139, 157). The results in general corroborated American findings and mentioned increased early strength by use of percentages of fly ash in excess of cement taken out of the mix, while stressing a mill-blended fly ash cement for the smaller jobs. Such blending had been advocated in 1950 by Blanks (58) and by Meissner (69) even for the larger projects.

This same year Fucik (147) reported using fly ash successfully and advantageously in the Guayabo Project, El Salvador.

Also in this year (1954), investigations by the National Ready Mixed Concrete Association were reported (141, 142), with essentially the same findings as those of previous workers.

The French, continuing the intensive studies on the finer grinding of fly ash to overcome the low early strengths, reported successful results (149, 169, 185, 211, 226, 242, 243, 244, 248).

Lilley in Great Britain (101) reported negative results on the use of fly ash in soil-cement mixtures.

Work in the United States continued with increasing stress on the various possibilities of fly ash and on its usefulness as a pozzolan (152, 153, 154, 155, 156, 159, 189, 224). By then, the production of fly ash had increased to such an extent that Weinheimer (158) felt that the problem of its disposal was becoming "mountainous."

In 1955, the British reported the increasing use of fly ash in bricks, in concrete, in building blocks, and in the manufacture of lightweight aggregate (161, 162, 163, 164, 165, 167, 181, 186)—lightweight aggregate being particularly advantageous because of the possibilities of manufacture close to the source of the fly ash.

About this time, the Corps of Engineers began reporting on a series of comprehensive testing programs. This extensive series of tests included the evaluation of various finely divided mineral admixtures, including several fly ashes. The whole series led to favorable results detailed in the various papers (170, 192, 218, 233, 246, 247, 272), and led to the first use of fly ash by this organization on Sutton Dam in West Virginia, as a 25 percent replacement on the basis of absolute volume. Contracts for the use of fly ash on more recent dams are understood to have been consummated.

The writer visited this project in August 1958 while construction was under way, and observed the operation. The main problem appeared to be the maintaining of control on air-entrainment by changing the quantity of air-entraining agent used as the carbon content of the fly ash varied.

As part of the Corps' comprehensive program, concrete blocks using mixes similar to those in dam construction and made with fly ash (45 percent by volume of the total cementitious materials), natural cement (35 percent by volume), and plain concrete control mixes, were made and cured at the Waterways Experiment Station 14 days wet, then outdoor exposure, spring to fall, and then exposed to salt water freezing and thawing at Treat Island, Maine, in the fall of 1953.

The writer had the opportunity of examining these blocks in July 1958. This examination indicates that the fly ash mixes are not standing up, in general, as well as the natural cement, or standard portland cement mixes. There is evident a great deal of scaling and corner raveling.

In 1955 also, India showed interest in fly ash, and as a starting point, reviewed the American and Australian work.

In July 1955, a pavement was built as an entrance to the St. Clair Power Plant between Marine City and St. Clair, Michigan, in which fly ash was used in the mix in different sections—in quantities both equal to and in excess of the cements taken out. This pavement was cured with white-pigmented curing compound, and opened to traffic at the age of 28 days. The fly ash used had 13 to 14 percent loss on ignition, and a fineness of about 3,100 square centimeters per gram. The use of fly ash in the higher proportions does not seem to have improved the early strength in this instance. This pavement carries heavy plant traffic, because of the hauling of fly ash to dumps, in heavy trucks. One section was a plain concrete control section. The pavement is salted during the winter months.

An examination of this pavement was made by the writer in July of 1957, or 2 years after construction. The pavement appears to be in good condition, with a few fine shrinkage cracks here and there. The beginning and end of the pavement show some surface wear, probably due to the grinding by traffic of sand and gravel from the adjacent roads.

This same year (1955), Japanese reports covering work with fly ash indicated their interest in the subject (173, 255, 260). By separating coarse particles from the raw fly ash, they were able to obtain a fineness of 5,790 square centimeters per gram. Their conclusions are essentially a corroboration of the over-all general findings in the United States and in other countries. In general, they obtained:

1. Lower water demand.
2. Better workability.
3. Low early strengths but high ultimate strengths.
4. Reduced drying shrinkage.
5. Adequate freezing and thawing durability with air-entrainment.

The Bureau of Public Roads published, in 1956, results of a comprehensive series of tests on 34 fly ashes in combination with three cements (182, 200). Again, these comprehensive tests corroborated the findings of previous investigators regarding the general beneficial effects of fly ash on concrete in which it is used.

Also in 1956, experiments at Kansas State College indicated the probability that a low limit on SO_3 in fly ash is not a prerequisite to good concrete (184).

A description of the large-scale use of fly ash on dam construction in Great Britain, appeared about this time (187, 253).

In 1956 also, Price (194) summarized the studies of the Bureau of Reclamation on fly ash, and its application to heavy construction.

This same year comprehensive studies were reported from Australia (205, 259), comparing Sydney fly ashes with results obtained in the United States, and with the previously published East Perth Station tests (173) in Australia. General agreement with earlier findings was found, except that the Sydney fly ashes had lower specific gravities (as low as 1.88), which resulted in higher water demand (110-130 percent).

In 1957, the Shippingport Atomic Power Station was constructed utilizing large volumes of fly ash concrete with 20 percent by volume replacement and Type IS cement

(220). The strengths obtained were generally equal to control at 80 days, but lower at earlier ages.

About the same time Peters (223) reported from Germany on the advantageous uses of fly ash in concrete.

In 1958 the Sixth International Congress on Large Dams brought together many papers covering experiences and results of investigations from all over the world—generally favorable to the use of fly ash in concrete (232, 237, 239, 240, 241, 247, 248, 253, 254, 255, 256, 258, 260). Among these, Dexheimer (237) (U.S.) reviewed the favorable use of pozzolans in general, and fly ash in particular, by the Bureau of Reclamation on various projects. He reported that fly ash had been used in four major dams, out of a total of 13 in which pozzolans were utilized, and was proposed for a fifth one. The only other pozzolan used on four dams was calcined shale, while pumicite and calcined clay had been used on two dams each.

Bertier (232) (France) offered an explanation of the mechanism of damage to concrete by freezing and thawing, and the unfavorable role of free lime. He concluded that this damaging effect can be reduced by fixing the lime in the concrete through the introduction of a suitable pozzolan.

Duserre (239) reported satisfactory experience on a French dam, utilizing 15 percent replacement with a fly ash having a 9 percent loss on ignition, and a fineness of 2,025 square centimeters per gram. Fouilloux (240) (France) reported on blended cements which develop early strengths comparable to standard cement, one being a combination of fly ash and portland cement clinker, and the other fly ash, blast furnace slag, and portland cement clinker.

Others reporting at this Congress included Kennedy (247) (U.S.), who summarized the Corps of Engineers' investigations, and concluded that properties of mass concrete need not be adversely affected by judicious use of replacements. Lafuma (248) (France), reported on the influence of grinding fly ash, and concluded that finer grinding improves the early strength. McDonald (253) reported on the use of fly ash in Lednock Dam in Great Britain, with ensuing favorable results. On this project accelerated curing with hot water was tried, but was not developed sufficiently to become reliable. Marshall (254) (Great Britain), found that increasing fineness of fine aggregate in fly ash mixes resulted in unchanged or decreased workability, and unchanged or decreased compressive strength. Mizukoshi (255) (Japan), reported results of use of fly ash on Sudagai Dam, and corroborated the general American findings. Morgan (256) (Great Britain), reviewed advantages of fly ash. Steopoe (258) (Roumania), outlined a very interesting hypothesis for the mechanism of pozzolanic action in hardened concrete. Yamazaki (260) (Japan), reported experimental results on raw fly ash, and fly ash from which the coarse particles had been separated, and corroborated the general findings from the United States.

Friis (241) summarized for the Congress the beneficial results reported for fly ash and pozzolans in 29 papers from 11 countries:

1. Better workability.
2. Lower heat evolution.
3. Decreased shrinkage.
4. Lower compressive strength at 28 days, but same at about 90 days.
5. Better frost resistance.

He concluded that chemical analyses are needed, suggesting that an international standard be set up.

Meanwhile the French had developed simple control tests to check the activity of fly ash, and to determine its proportions in cement samples in which fly ash has been interground (242, 244).

With the disposal of French fly ash becoming a more critical problem, Jarrige (243) reviewed the whole subject, and various possible applications as measures to utilize fly ash.

Karpinski (245) (still in 1958), claimed that the water-cement ratio had an effect on pozzolanic activity and gave a method to correct for this.

Tennessee Valley Authority investigators (249, 250, 251), reported on the successful use of a coarse fly ash with a fineness of 2,000 square centimeters per gram in a structure. The mix utilized 30 percent replacement by weight of cement, plus 8.5 percent replacement of the sand.

The writer visited the work on this lock in February 1958, and was impressed by the smooth surfaces and sharp corners and grooves formed into the concrete. Concreting operations could not be observed because of a shutdown due to unexpected cold weather.

Fly ash has been used in grout mixtures (158, 246) but it is not clear when such use began.

Lovewell and Washa (252) published more data in 1958, indicating that use of fly ash in excess of the amount of cement reduction improves early strength.

The same year Polivka and Brown (257) reported on a method of evaluating resistance to sulfate solutions, and found that fly ash performs well as compared to other pozzolans.

In 1959, the American Society for Testing Materials (261) approved a standard for determining the effectiveness of mineral admixtures in preventing excessive expansion of concrete due to alkali-aggregate reaction.

Bauer (263) summarized advantages of pozzolans as buffers in concrete mixes, and attempted to show incentives for the cement industry to manufacture pozzolanic cements. He stressed advantages for a pozzolan industry association.

Hansen (268) reported early in 1959 that fly ash releases alkalies to the liquid phase of the hardened cement paste and should be taken into consideration when used with aggregates that are known to react with alkalies.

Minnick (271) reported at the 1959 ASTM Annual Meeting on studies made on fly ash in an effort to evaluate results from chemical analyses, physical tests, X-ray diffraction, fluorescent spectrographic analyses, microscopic examination, and differential thermal analyses. He concluded that the differential thermal analysis correlated with strength or X-ray data may prove a useful tool for initial evaluations.

Pepper and Mather (272), also at the 1959 ASTM Annual Meeting, reported further on the continuing series of investigations by the Corps of Engineers and gave minimum quantity of each material required in the mixes to prevent excessive expansion in test bars due to alkali-aggregate reaction. These quantities ranged from 10 to 45 percent.

Also in 1959, the Bureau of Reclamation summarized (273) studies on the release of alkalies from various combinations of pozzolans and lime, as compared to the expansion in pyrex mortar bars in which the same pozzolans had been used. No apparent relationship was found between the amount of alkalies released and the expansion developed by the bars.

BLOCK, PIPE, PRECAST, AND PRESTRESSED UNITS

These products, although made of portland cement, have problems and properties so much in common and yet differing from concrete placed in forms at the construction site, that they deserve further discussion by themselves. All that has been said about concrete applies as well to these products, in varying degrees. The distinctive properties that set them apart from general concrete construction are:

1. They are made in yards or plants under "industrial manufacturing conditions" that permit closer control than on the construction job.
2. The processes are repetitive, the end result being duplicate units produced over and over again.
3. Curing is usually at elevated temperatures using saturated steam to produce heat and at the same time to maintain high humidity conditions.

Most such concrete products are made with very dry mixes, tamped or vibrated in molds or forms. The stripping of molds or forms as fast as possible is an economic advantage in making the forms available for repeated use. The improved green dry strength of fly ash mixes which permits handling very soon after molding is therefore advantageous (62).

Sharp corners, fine mold detail, and smooth surfaces obtained by adding fly ash to the mix, make a better appearing product (12, 35, 39, 62, 114, 199, 206) that has superior sales appeal, and in the case of blocks results in a better looking finished wall. Fly ash reduces the porosity of cinder block (12). Because of the repetitive nature of the production of these items, a small saving in the mix develops into worthwhile reduction in total cost.

The use of fly ash in concrete mixes for precast products thus has multiple advantages (119, 206), among which are:

1. It permits a drier mix to be used, or provides a more workable mix for the same amount of water (62, 206).
2. Because it holds the water in the mix and reduces bleeding, less sand streaking occurs, particularly in pipe and precast units.
3. It provides a better green strength, thus permitting earlier stripping and handling of the units (62, 238).
4. It reduces wear on molds and machinery (114, 206, 238).
5. It provides better finish and better corners, thus enhancing the appearance (39, 62, 206, 243).
6. It permits a reduction in cement in many instances that will result in appreciable over-all savings.
7. In block mixes 20 percent fly ash in the mix has been found to give equal of greater compressive strength (54), and a volume change essentially the same as mixes without fly ash. Replacement in excess of cement reduction is beneficial (199).
8. Because of the higher moist curing temperatures, pozzolanic action takes place faster, and results in higher early strength gains than under ordinary curing temperatures, thus eliminating the early low strength criticism frequently leveled at fly ash concrete (35, 39, 206, 226).
9. Pipe made with fly ash mixes has the additional advantages of improved resistance to sulfate, and reduced permeability and leaching (145, 199).

Over-All Conclusions (Portland Cement Concrete)

This section is essentially an objective summary of the effects of fly ash in concrete in the light of present-day knowledge. It attempts to combine the various findings in the published literature and observations on the various projects that were studied, into a set of over-all conclusions. Some of these conclusions are definite enough to justify positive statements in the light of today's knowledge of the subject, while others warrant only an expression of trends.

In evaluating the use of fly ash in concrete, the views of the various authors, shown in the list of references and highlighted in previous sections, are combined with personal observations of the writer from visits to the various projects and from discussions with organizations and individuals using fly ash, testing it, or conducting research on it.

Although there are conflicting reports and opinions on the properties of concrete in which fly ash is used, the following characteristics are reasonably well confirmed by the studies and experience on the jobs, and may be accepted as a reasonable consensus of available information to date. These characteristics vary in degree with the source of fly ash, but may be accepted as applying in general to those fly ashes that come close to meeting the requirements of specifications such as those issued by the Bureau of Reclamation, Corps of Engineers, American Society for Testing Materials, Bureau of Public Roads, and similar specifications that have been issued by experienced users. Some fly ashes outside the limits of such specifications will have similar influence on the properties of concrete in which they are used, but each case must be judged on its own merit through tests simulating the conditions under which the material is to be used. The reason for the need of such tests is that no single characteristic of fly ash or simple combination of characteristics controls its performance in concrete (19, 20, 179).

RAW FLY ASH

Specifications

Many of the large organizations using fly ash have suggested or issued specifications which have been published (3, 60, 87, 91, 135, 148, 149, 153, 168, 182, 194, 231, 237, 247). The latest Bureau of Reclamation specification is given here as an example:

CHEMICAL COMPOSITION

Silicon dioxide (SiO_2) plus aluminum oxide (Al_2O_3) plus ferric oxide (Fe_2O_3), not less than	75.0 percent
Magnesium oxide (MgO), not more than	5.0 percent
Sulfur trioxide (SO_3), not more than	4.0 percent
Loss on ignition, not more than	5.0 percent
Moisture content, not more than	3.0 percent
Exchangeable alkalies as Na_2O, not more than	2.0 percent

PHYSICAL PROPERTIES

Fineness:	
Specific surface, square centimeters per gram (air permeability fineness method of test), not less than	3,000
Material retained on No. 325-mesh sieve, percent, not more than	15
Compressive strength:	
With portland cement, percent of control, 28 days, not less than	85
With lime, 7 days, minimum pounds per square inch	900
Change of drying shrinkage of mortar bars, percent shrinkage of pozzolan bar minus percent shrinkage of control bar, not more than	0.04
Water requirement, not more than	103.0 %

Note: The specific gravity of individual samples from any one source shall not vary more than 3 percent from the average established by the 10 preceding samples or by all preceding samples if the number is less than 10.

REACTIVITY

Reduction of expansive reaction at 14 days, not less than	75 percent[1]

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[1] This requirement may be reduced on specific jobs when alkali-aggregate reaction is not considered to be an important factor.

Other organizations such as the Corps of Engineers, Bureau of Public Roads, and American Society for Testing Materials have similar requirements, with minor changes in the limits, the most significant of which is perhaps the loss on ignition, which can be a maximum of 12 percent in ASTM, and the fineness, which can be as low as 2,800 square centimeters per gram in the same specification.

Chemical Properties

Though fly ashes are produced from coals of widely different origin, the differences in the chemical composition do not appear to have a marked effect on the concrete properties except for variations in carbon content (3, 38). Chemical composition alone may not, however, be a sufficient criterion regarding the suitability of fly ash, as the condition in which the chemicals are found affects the action of the fly ash (149). Carbon content is affected by the source of coal, the type of combustion equipment, conditions of combustion, constancy of load, and method of collecting the fly ash (65, 81). Carbon content, with its variable particle size and surface particle conditions, and differences in its activity, is perhaps the most significant factor affecting the suitability of fly ash for use in concrete (3, 38). Methods of separating the carbon particles or reducing their proportion are available, but are not commonly used (152). The effect of carbon content on the concrete properties is not specifically known, but it does affect air-entrainment and the amount of air-entraining agent required to maintain a given level of air content.

Most investigators agree on the need for low lime fly ash for optimum effectiveness (60, 211), but Breckenridge (208) used high lime fly ash successfully in concrete mixes.

Carbon Content

This is one of the most controversial constituents of fly ash in its application to concrete work. No one appears to know definitely whether it has any harmful effects but most users require low-carbon fly ash. Most investigators feel that it is the most significant factor affecting the suitability of fly ash for use in concrete. The higher carbon fly ash should be used only in small percentages in concrete mixes. Carbon in fly ash does not seem to affect weathering resistance (3, 13, 38, 61, 79, 119, 139, 149, 153, 157, 182, 191, 194, 205, 236, 260).

It has been repeatedly established that carbon affects the amount of air-entraining agent required to maintain a given level of air-entrainment (51, 74, 117, 137, 141, 187, 191, 194, 200). Therefore, control of carbon content in the fly ash for a given project is desirable in order to minimize the problems of controlling the concrete mix (37, 42, 136, 187).

As an organic material, carbon may possibly have a deleterious effect on concrete in the same manner as any other organic compound—it has been standard practice to limit such compounds in aggregates, particularly in sand. Yet Frederick (29) found that carbon content had no deleterious effect on strength.

A very good possibility is that it acts as a diluent of the active pozzolanic materials in fly ash, and thus becomes one of the factors affecting the rate of pozzolanic action, and therefore the rate of development of early strength in concrete (270). Strength loss with inert material replacing carbon is not as high as with the carbon present (187).

Whatever the reasons for carbon being looked upon with disfavor in fly ash used in concrete, it seems to be a well-established practice to limit it to relatively low percentages in all specifications where the fly ash is to function as an ingredient in the concrete mix. The maximum carbon content in present-day specifications varies from 5 to 12 percent, depending on the specifying agency.

There appears to be no logical reason for limiting the carbon in fly ash used for lightweight aggregate, bituminous filler, and other similar applications, as long as it does not exceed reasonable proportions.

SO_3 Content

Although all specifications limit the SO_3 in fly ash to a relatively low maximum (in the same manner that it is limited in cement), work at Kansas State College, reported by Chubbock (184), and in Germany by Kronsbein (20), indicates that this compound may not be as harmful in the final fly ash concrete as has been generally supposed. The sulfur compounds in fly ash are found in lesser amounts than in slag (84). Increase in carbon appears to increase SO_3 content (187).

Physical Properties

From microscopic studies, it is known that the incombustible particles in fly ash are generally spherical in shape, while the carbon particles are coarser and irregular in shape, porous, and cokelike (152). The Blaine fineness varies with the source, but it is usually between 2,000 and 6,000 square centimeters per gram. Generally, the higher the carbon content, the lower the percentage of fines in the fly ash, even though the specific surface reading may be higher due to the porosity of the carbon particles. In general, fly ash used in concrete is finer than the cement it is mixed with.

Because of its fineness and rounded particle shape (it flows like "liquid smoke"), fly ash handling presents problems of dust and requires very tight conveying equipment—all of which creates some sales resistance (31, 53, 78, 262).

The specific gravity of fly ash varies from 1.88 to 2.84, and in general, the finer particles have the higher specific gravities. Its bulk density depends on the variations in specific gravity. Chicago fly ash has a density of 70 to 75 pounds per cubic foot as compared to 94 pounds per cubic foot for cement.

Fly ash should pass the standard soundness test when mixed with cement, to guard against delayed expansion (13).

The heat conductivity of bulk fly ash has been found to be 0.74 Btu per inch per square foot per degree Fahrenheit at 75° F, and 1.04 at 356° F. This compares with 0.01 Btu per inch per square foot per degree Fahrenheit at 200° F for asbestos (31).

Fineness

Fineness is one of the principal variables affecting the suitability of fly ash in concrete (3, 13). Fineness of fly ash is usually expressed in terms of specific surface rather than by sieve sizes.

The desirable fineness of fly ash appears to be practically as controversial as the carbon content. There is reasonable agreement that the finer the fly ash, the better it is for use in concrete mixes. Many investigators, particularly the French (who have ground fly ash to a fineness of 12,000 square centimeters per gram), indicate that the increased fineness leads to accelerated pozzolanic activity and thus to higher early strength—a logical consequence, since most chemical reactions proceed faster with increased fineness (3, 13, 79, 149, 153, 169, 182, 187, 191, 205, 211, 226, 238, 240, 243, 248).

Pozzolanic Properties

Fly ash in general exhibits high pozzolanic properties when used in concrete mixes (3, 31, 45, 60, 61, 73, 111, 139, 149, 185, 188, 193, 194, 201, 205, 211, 226, 233, 236, 270). Pozzolanic activity varies with the source of fly ash, and various tests have been developed to evaluate its potential. Usually, the finer the fly ash and the lower the carbon content, the greater the pozzolanic activity, and therefore the greater the contribution to the strength of the concrete. Cements of normal or high lime content are best for use with fly ash (3, 243). Methods of determining activity of a pozzolan have been proposed by several investigators (21, 72, 87). Pozzolanic activity is influenced by chemical composition and the condition in which chemicals are present. Materials high in silica and low in alumina react slowly at normal temperatures but much more rapidly at elevated temperatures.

FLY ASH IN CONCRETE MIXES

Fly Ash Content

The optimum amount of fly ash to use, in mixes adjusted to obtain cement reduction, depends on so many factors that for large projects it is best to determine the proportions by actual tests using the proposed cement and aggregate. Fly ash used in this manner in the past has been from about 20 percent by weight or absolute volume of the original cement in the mix, to as much as 50 percent (3, 13, 19, 60, 79, 101, 128, 157, 177, 182, 187, 191, 197, 204, 205, 206, 218). Where the mix adjustment is made to obtain sand reduction, maintaining the cement content the same, Frederick (29) found the optimum to be 25 percent of the weight of the sand. If used in too small a quantity, fly ash may induce alkali-aggregate reaction (177).

The higher proportions work well in mass concrete of leaner mixes, where reduction of heat of hydration is important due to the heavier sections, and where early strength is relatively unimportant, or in protected concrete such as foundations and inside buildings (13); while the lower quantities are better in smaller structures with richer mixes and thinner members where heat of hydration is relatively unimportant, and in which early strength becomes an important factor. In any case, there seems to be agreement that the leaner mixes can profit by higher optimum replacements than the richer mixes.

In mixes in which fly ash is used in quantities in excess of cement reduction, the percentage used may be higher yet, but a part of this is considered as taking the place of sand fines, or as an admixture. In such cases, the total fly ash may be as high as 50 percent of the original cement content—considered as about 25 to 35 percent to replace cement, and the balance to take the place of part of the sand and to act as an admixture (3, 12, 18, 29, 51, 101, 136, 146). Stickiness, rubberiness, or gumminess, reported in the mixes with the higher fly ash quantities, may be remedied in most cases by a proper redesign of the mix and modification of handling and placing procedures. Efficiency of cement is increased by addition of 10 to 15 percent fly ash and adjusting mix to reduce cement (92).

Water Requirement

Most studies lead to the conclusion that fly ash used as an admixture or as a replacement in optimum amounts does not increase the water requirement of the mix. In fact, with fly ashes of high fineness and low carbon, a reduction in water demand often results due probably to the rounded particle shape. However, the coarser fly ashes with higher carbon contents usually increase the water requirement slightly (3, 58, 60, 61, 79, 97, 111, 177, 260).

Workability and Plasticity

Fly ash, used in properly adjusted concrete mixes, improves the workability and plasticity of concrete mixes. This fact has been confirmed repeatedly and has become almost axiomatic (3, 58, 60, 61, 79, 97, 111, 139, 154, 187, 194, 201, 206, 241, 259). This property is a great advantage in the harsher mixes, particularly in the manufacture of building blocks, and in lightweight aggregate concrete. Pound for pound, fly ash is a better workability agent than cement (1, 6, 10, 106). As an admixture, without reduction in cement, but with an adjustment of the sand in the mix, fly ash improves the workability more than when the cement is reduced (29).

Fly ash concrete is reported to be more satisfactory when placed by pumping than plain concrete under the same circumstances.

Segregation

Fly ash in concrete mixes reduces segregation. Like improved workability, this has been confirmed by so many independent investigators that it seems trite to repeat it (3, 60, 61, 79, 201, 259). This property of fly ash is particularly helpful in the lightweight aggregate mixes such as those using Haydite (12).

Bleeding

Fly ash in concrete mixes reduces bleeding. This again, has been observed repeatedly and has become an established fact (3, 18, 29, 48, 53, 60, 61, 69, 79, 91, 116, 117, 201). Powers (15) advances a hypothesis that the addition of fines to a concrete mix is one way to reduce bleeding—possibly the very fine particles in fly ash act effectively in this manner. Moran (154) also gives a theoretical discussion on bleeding.

Time of Set

Fly ash generally slows the setting time of cement, but as a rule the times of setting remain within the usual specification limits (3, 226, 238).

Heat of Hydration

Raw fly ash generates about 40 to 50 percent as much heat of hydration as the cement it usually replaces. Therefore, when used in concrete with a resulting decrease in cement content, the net effect is a lower heat of hydration of the total mix (3, 58, 60, 61, 79, 97, 136, 187, 191, 194, 201, 211, 226, 238, 241, 243, 260). However, when used in excess of decreased cement content, this advantage is reduced, and may, if used in large enough quantities, develop a heat of hydration equal to that of an equivalent plain concrete mix. It is not likely that the excess fly ash will be used in such a quantity as to increase the over-all heat of hydration of the mix as compared to the plain concrete, because the concrete will become too gummy and sticky to handle before this point is reached.

In the case of interground fly ash, French investigators have found that the finer the grind the less advantage fly ash has in lowered heat of hydration, and eventually in the finest grinds attempted (close to a fineness of 10,000 to 12,000), the heat of hydration of the mixture is about equal to that with the mix using plain cement (226, 243).

In dams, reduced heat of hydration decreases the required artificial cooling, in addition to lowering thermal shrinkage and reducing cracking. This permits larger blocks to be used and thus speeds up construction.

In Hungry Horse Dam, it has been estimated that the heat drawn from the dam during construction, by circulating cold water in pipes embedded in the concrete, is equivalent to the heat obtained by burning 5,500 tons of coal (57).

FLY ASH IN HARDENED CONCRETE

Curing

For best results, fly ash concrete requires moist curing for long periods in order to develop maximum pozzolanic properties (191, 201). This extended moist curing can be shortened and still achieve the same end results, by:

1. Increasing the amount of fly ash, and therefore the amount of active pozzolan in the mix, thereby getting more concentrated pozzolanic action in a shorter period (3, 18, 199, 243).
2. Intergrinding the fly ash with the cement clinker, resulting in a finer fly ash—more intimately and uniformly mixed with the cement—again accelerating the pozzolanic action through the more active finer particles (3, 21, 226, 243).
3. Higher temperature curing, particularly by steaming or autoclaving—the higher temperature accelerates the pozzolanic activity (35, 37, 39, 59, 89, 149, 198, 221, 226, 243).
4. Addition of slag or cement germ that has set, which act as accelerators (243).

Volume Change and Shrinkage

Fly ash used in concrete continuously fog cured, increases expansion slightly (60, 132). However, it tends to decrease drying shrinkage (3, 58, 61, 79, 194, 200, 201, 226, 241, 243, 260). Fly ash has a tendency to retard autogenous shrinkage at early ages (136) and to increase autogenous shrinkage at later ages in rich mixes (132). Autogenous shrinkage of lean mixes containing fly ash compares favorably with control mixes (136). Because of the lower heat of hydration of fly ash concrete, and therefore the lower temperature rise in concrete members, the thermal shrinkage is decreased (47, 48).

Extensibility and Plastic Flow

Indications are that fly ash concrete possesses increased extensibility and plastic flow as compared to plain concrete (47, 48, 60, 69). These properties at early ages are conducive to decreased cracking due to drying shrinkage (3, 57, 109).

Molding Qualities

Fly ash in concrete mixes appears to produce smoother formed surfaces, and sharper form details and corners. This is particularly advantageous in architectural work, in building blocks, and in precast members (12, 62, 114, 199, 206).

Compressive Strength

The use of fly ash is more effective in increasing strength in lean concrete mixes than in rich mixes (53, 60, 61, 79, 134, 182, 201).

For standard moist curing conditions (70° F), fly ash of high fineness and low carbon content, used in mixes which are adjusted by the reduction of cement on an equal quantity basis, results in lower compressive strengths at early ages (up to about 90 days) but produces much higher ultimate strengths, due to the pozzolanic action at later ages (3, 19, 45, 58, 60, 61, 79, 97, 139, 188, 194, 200, 205, 226, 235, 238, 241, 243, 259, 260). Occasionally there is a report that the early strength is as good as or exceeds the plain concrete (32). The early strength of fly ash concrete is very sensitive to cold weather (226).

As an admixture without reduction in cement, but reducing the sand by 25 percent, the 7- and 28-day strengths exceed those obtained by using plain concrete. For a specified 28-day strength, and 25 percent reduction in sand, there is a saving of 34 to 48 percent of cement over plain mixes (29).

Grinding fly ash to a greater fineness (21, 226), intergrinding it with cement (3, 53), or with portland cement clinker (121, 149, 211, 226, 240, 248) increases the early strength—in many cases to a level equivalent to that obtained with portland cement alone. Intergrinding with blast furnace slag and portland cement clinker results in outstanding early and later strengths.

Experience since 1954 indicates that fly ash used in excess of the reduction of cement, also has the effect of raising the early compressive strength. This depends again on the mix, the materials in the mix, and the excess of fly ash (18, 53, 98, 101, 114, 119, 123, 137, 139, 198, 252, 259).

Under mass curing conditions (70° F for one day and then 100° F), fly ash concrete develops greater strength than the corresponding portland cement concrete, even at the early age of 28 days (3). Under higher temperatures such as steam curing, fly ash concrete develops early strength rapidly (226).

The increased early strength due to intergrinding, to the addition of fly ash in excess of cement reduction, or to the higher curing temperature is probably the result of increased pozzolanic activity due to the finer particles, the larger proportion of pozzolanic active materials, or the higher temperature, respectively.

Davidson and his associates (267), found that the addition of trace chemicals to mixtures of Ottowa sand, lime, and fly ash activates the lime-fly ash reaction, and thus increases early strengths. An addition of 0.5 percent of powdered sodium carbonate to the mix, increased the 7-day strength about 60 times, and the 28-day and 4-month strength about two times.

Wallace and Ore (275), found that the use of water reducing retarders used in concrete mixes containing fly ash increased strengths at all ages.

Flexural Strength

Little information is available on the effect on the flexural strength of fly ash in concrete mixes, and what information is available is somewhat conflicting. In general, it appears to follow the same trends as the compressive strength; that is, that the early strengths are lower than the corresponding portland cement concrete, but after the age of 28 or 60 days is reached, pozzolanic action influences the strength, and results in higher ultimate strength (51, 77, 117, 132, 134, 200, 211, 226). Tensile strength of concrete is increased by fly ash (48, 109, 243), and inasmuch as the flexural strength depends on tensile stresses, one might be justified in concluding that fly ash may improve the flexural strength as compared to plain concrete.

Modulus of Elasticity

The modulus of elasticity of fly ash concrete is lower at early ages, and higher at later ages (3, 60). In general, fly ash increases the modulus of elasticity of concrete when concretes of the same strength with and without fly ash are compared (132, 134, 136).

Abrasion

There is some indication that fly ash concrete may not be as resistant to abrasion as ordinary concrete (129, 132, 191). The lean mixes used in dams seem to be definitely so, but no reliable data are available on the richer paving concrete. Visual observations by the writer on several experimental pavements are inconclusive.

Permeability

Fly ash has been found repeatedly by several investigators to decrease the permeability of concrete mixes in which it is used about 6 to 7 times, and thereby reduce leaching (3, 31, 58, 60, 61, 79, 136, 146, 191, 194, 201, 211, 238, 245).

RESISTANCE TO ADVERSE CONDITIONS

Alkali-Aggregate Reaction

Most fly ashes, when tested in expansion mortar bars, show reduced expansion from the alkali-aggregate reaction in varying degree, depending on the cement, the aggregate, and the fly ash used (31, 45, 58, 60, 61, 79, 111, 122, 182, 188, 191, 194, 201, 205). In the presence of calcium chloride its effectiveness in this respect is reduced (177). Portland Cement Association tests (81), on the other hand, indicate that abnormal expansion occurs in fly ash mortar bars.

Tests for determining the reduction of expansion from alkali-aggregate reaction by the addition of an admixture have been proposed by various investigators. The most reliable test appears to be the mortar bar expansion test, which has been standardized by the American Society for Testing Materials under Designation C 441-59T (72, 100, 233, 261, 272).

Many explanations have been given to show how fly ash inhibits the expansion in the mortar bar test for potential alkali-aggregate reaction. It is a subject about which little is known with any degree of certainty. The explanation given in (111) probably best fits experimental observations and experience with pozzolans to date. The additional following notes represent the ideas proposed by various investigators in an attempt to explain the experimental findings.

Some investigators feel that the presence of alkalies in fly ash may be beneficial (60, 211), even though others find that such alkalies can be leached and therefore may enter into the over-all chemical reactions in the concrete (268, 273).

Fineness of pozzolan, the dissolved silica, and the percentage of alkali retained by the reaction product correlate with the effectiveness of the pozzolan in inhibiting alkali-aggregate reaction (233).

The alkalies in fly ash may be in a less available form than in cement, which could account for the fact that these alkalies do not produce the same reaction with aggregates as alkalies in cement do. Yet, there is evidence that at times more alkalies are released from the pozzolan than from the cement. Possibly, the pozzolanic properties of fly ash may be used partly to overcome the effect of its own alkalies, and partly to compensate for the deleterious effect of the alkalies in the aggregate.

The alkali-aggregate reaction results in the development of alkali-silica gel complexes which are capable of absorbing water and swelling, thus creating substantial pressures that contribute to the development of cracks in the concrete. The capacity of such gels to absorb water is controlled by the alkali to silica ratio. If this ratio is small (that is, too little alkali), the combination will not absorb water and therefore will not swell. On the other hand, if this ratio is too high, the gel readily dissolves in water and is dispersed through the cement paste. When the alkali-silica ratio in the gel is in the intermediate range, it results in gels capable of absorbing water and developing the expansion that is deleterious to concrete. The range of this ratio in which such deleterious action can take place is variable and only ambiguously defined, which accounts for much of the uncertainty in this phase of concrete technology. There seems to be lack of agreement as to whether the alkalies in the pozzolan do or do not participate in all these reactions, and if so whether such participation is advantageous or detrimental. In most instances, the end result appears not to suffer from the presence of alkalies in the original pozzolan (111, 263, 273).

The glassy phase of fly ash is most effective in overcoming the alkali-aggregate reaction, and some fly ashes contain more of this phase, while others have a larger proportion of the crystalline phases which are less effective for this purpose.

Progressive activity of alkali-aggregate reaction requires presence of lime to liberate the alkalies from the alkali silicates. Fly ash and other pozzolans can tie up this lime, and thus prevent it from releasing the alkalies from their silicates (122).

Some tests indicate that about 20 grams of finely divided reactive silica are required per gram of alkali in the cement in excess of 0.5 percent, to inhibit the alkali-aggregate reaction (202).

Cement-Aggregate Reaction (Sand-Gravel Aggregate)

In the Great Plains area where coarse aggregate is scarce or nonexistent, the use of sand-gravel aggregate (with very little material larger than the ¼-sieve size), as a total aggregate, is prevalent. In Kansas and Nebraska where this practice is common, severe map-cracking patterns develop in a few years (the critical period being 7 to 10 years after the concrete is placed), that is not entirely attributable to alkali-aggregate reaction.

Many additions including up to 30 percent of imported crushed limestone coarse aggregate, and various pozzolan combinations have been tried. Although none of the treatments tried to date appear to solve the problem entirely, some of the additions are effective in delaying or reducing this deterioration. One of the most promising of these additions appears to be fly ash, and there is some conjecture that fly ash in combination with a small amount of crushed limestone coarse aggregate may prove to be a complete solution (74, 87, 108, 117). Three test roads in Kansas and Nebraska are being watched with interest, as they are at present going through the critical period.

Corrosion

The question has been raised as to whether the sulfur content of fly ash might promote corrosion of reinforcing steel. The sulfur content of fly ash is limited by specifications and is of the same order of magnitude as that found in cement, so that there is no general over-all increase of sulfur in a concrete mix in which fly ash has resulted in decrease of the cement content. Corrosion is affected by the pH of the surrounding material and is very slight in a high pH environment. Inasmuch as moist concrete exhibits a very high pH, of 12 to 13, little or no corrosion can be expected (80, 86).

The lime in the concrete reacts with the iron in the steel, resulting in a protective film of ferrous hydroxide. In addition, the impermeability due to the pozzolanic action of the fly ash, would prevent or minimize penetration of water and oxygen—necessary elements for corrosion. As for corrosion due to electrical currents, the carbon in the fly ash would theoretically be more likely to affect corrosion (increased conductivity) than sulfur. However, the low limitations on carbon in fly ash specifications, and the fact that it is so well dispersed in properly mixed concrete, would make its effect in electrical conductivity quite minor, and should therefore not be a factor in corrosion (86). Japanese work (269), indicates that the damage from electrolytic corrosion to concrete containing fly ash, is generally overestimated, and that it can be inhibited (where it is likely to occur), by the addition of calcium lignosulfonate to the concrete mix. The French claim that fly ash cement improves the resistance of concrete to electrolytic corrosion (211).

Freezing and Thawing

There are many conflicting and contradictory viewpoints on this subject, and apparently conflicting data obtained by various investigators. The principal reason for such conflicting evidence is because of the different curing methods used, up to the age of testing, as well as the differences in the freezing and thawing cycles employed (210). Powers (175), proposed a completely new approach to this test, but it has not gained wide acceptance as yet.

The most reliable evidence seems to point to the fact that with proper curing and air-entrainment, fly ash concrete exhibits very satisfactory and adequate durability, as measured by laboratory freezing and thawing tests, even though such durability may be lower than that of plain concrete in some cases (3, 19, 58, 60, 61, 79, 110, 187, 191, 200, 237, 241, 258, 260). To equal or exceed normal air-entrained concrete in durability, fly ash concrete has to be wet cured for about 80 days, a procedure rarely practical.

There is evidence, however, that if fly ash concrete is dried at a very early age, and then subjected to freezing and thawing, the durability falls off and is much lower than that of plain concrete treated in the same manner (110, 134). But if the drying takes place in a 50 percent relative humidity atmosphere, no such reduction in durability is observed, or at least the reduction is still within acceptable limits (110, 136).

It also appears that fly ash improves the freezing and thawing resistance of air-entrained concrete containing calcium chloride even though it reduces the effectiveness (early strength gain) of the chloride. A possible mechanism of the improvement of freezing and thawing resistance of concrete by the use of pozzolans is advanced by Berthier (232).

Resistance to Salts

Unfortunately the record is not very definite on this phase of the subject. Experiments of various types have been conducted, but none have been conclusive. Actual pavements in service seem to provide conflicting answers, principally because variables cannot be isolated.

There seems to be at least an indication that fly ash concrete may be less resistant in this respect than plain portland cement concrete, but the evidence is not sufficient to warrant a definite conclusion. With some cements, particularly the blast furnace slag cements, fly ash appears to improve their resistance to salts. It is to be noted that air-entrained concrete without fly ash shows at times unexplainable lack of resistance to salts also (32, 94, 200).

Resistance to Sulfates

It has been shown by various investigators that fly ash increases the resistance of plain concrete to the actions of sulfate water, mild acids, and active waters (3, 22, 58, 60, 61, 79, 139, 187, 191, 201, 211, 226, 238, 245, 257, 258, 260).

MISCELLANEOUS

Grouting

Grouting properties of mixes using fly ash have not been established. An excellent laboratory study reported by Kennedy (218, 246) utilized controlled artificial fissures and several materials, among which was fly ash. It appears that fly ash has some beneficial and some not as desirable properties (49, 53, 149, 154, 211). More work is needed to determine the place of fly ash in the field of grouting.

Lightweight Concrete

Fly ash contributes workability and reduced segregation in lightweight concrete mixes (12). In Europe aerated concrete—a lightweight concrete which obtains its lightness from air voids or gas voids—has been made successfully with fly ash (88, 104, 118, 143, 149, 225).

In this country, "Durox" plants manufacturing lightweight blocks, slabs, and beams, can utilize fly ash where it is readily available. Some of these plants are, in the absence of available fly ash, grinding silica sand to rock flour, and using it instead to obtain pozzolanic action.

Fly ash can be used as the fine aggregate in cinder concrete (43). Fly ash and blast furnace slag mixtures high in calcium sulfate and low in lime produce lightweight concrete of good strength (222).

Oil Well Sealing

The Halliburton Company developed the use of fly ash for oil well sealing, as a 50-50 blend with cement (109). This use is well established in oil well work.

Raw Material for Portland Cement

Fly ash has been used successfully and economically as a raw material in the manufacture of cement. This has been particularly true in Europe (20, 113, 187, 211, 213, 216, 225, 226, 230, 238, 243). In the United States, the writer knows of only two such applications.

Essentially, it is a question of whether the silica, alumina, and iron as raw materials for cement, can be obtained more economically from fly ash or from other sources.

Evaluation

The preceding section gave an objective summary of the effect of fly ash on concrete properties, in the light of present-day knowledge. In contrast, this section is an evaluation of the use of fly ash in concrete based on the foregoing findings, supplemented by examination of structures in service, visits to various research laboratories, and discussions with investigators in this field of concrete technology—all presented in the light of the writer's experience and judgment.

It is an attempt to assess the usefulness of the various findings, and their respective values in this field, in order to sift the reliably established factors from the less certain findings, and from trends and conjectures. Such an evaluation will focalize the research and development needs, and will permit the formulation of a research plan that will provide the required information. The results of such research will permit the full realization of the potentialities and advantages that result from the use of fly ash in the general field of concrete. This in turn will provide the utmost use of a costly waste product, and turn the disposal cost into a revenue and an asset.

BITUMINOUS CONCRETE AND BITUMINOUS PRODUCTS

It appears to be reliably established that fly ash can be used successfully and advantageously as a filler in bituminous concrete mixtures and in bituminous industrial products. Its principal competition at present is limestone dust, which is relatively expensive to produce, but already well established. Where fly ash is available in the same area, the fly ash will be by far the more economical product.

Its future competition (waste products also) will be the rejects resulting from the artificial production of lightweight aggregate from expanded shale and clay. These waste materials will require grinding, as in the case of limestone. Other filler materials are either not abundant, or will require processing, so that this leaves fly ash definitely in an advantageous position—a position that can be realized by proper promotion and aggressive salesmanship to overcome the fact that the competition is already established. Such concentrated efforts should develop a very healthy market for this use, over widespread areas.

This potential use of fly ash in bituminous concrete in highway and airport paving is very large, when it is realized that the percentage of mineral filler in a high type bituminous concrete mix is generally higher than the percentage of asphalt. The situation is particularly favorable on projects located close to sources of fly ash. No definite or reliable statistics on the total tonnage of asphaltic concrete, utilizing filler, are available, but asphalt cement used in all asphalt paving work is known to be about 8 million tons per year. Assuming conservatively that only between $1/5$ and $1/6$ of this asphalt is used in high type bituminous concrete utilizing filler material, then about 1,500,000 tons of asphalt are being used in this type of pavement. Again estimating conservatively that the filler is equal in weight to the asphalt used, gives an estimated filler market of 1,500,000 tons. If fly ash as a filler can capture half or two thirds of this potential, it would account for about 1,000,000 tons.

Some bituminous concrete is made with lightweight aggregate. Although there is no logical reason why fly ash lightweight aggregate would not be satisfactory in this application, there is no information available on this subject. Again the information regarding the quantities of such asphaltic concrete is not available but if found acceptable in this service, fly ash lightweight aggregate might account for the disposal of an additional appreciable volume of fly ash. In this case, because this would be a new fly ash application, some research will be needed to establish the adaptability of fly ash lightweight aggregate for this service, once such aggregate becomes commercially available in this country.

In bituminous products, such as roofing, filled mastics, plank, and similar commodities, there ought to be a good outlet, even though the quantities would be smaller than in the paving field. Plants for such products are usually in areas where fly ash is available, which is an economic advantage. A very important benefit of marketing fly ash for bituminous products is the year-round operation of such plants, in contrast to the seasonal nature of construction work applications.

LIGHTWEIGHT AGGREGATE

This phase of fly ash utilization does not seem to have gained momentum in this country. The Sinter-Lite Corporation, mentioned previously, is the only commercial operation that has come to the writer's attention. The British experience in making "Terlite" using a vertical kiln is reported commercially successful, but the experimental work in Canada using a rotary kiln indicates that results are very sensitive to variations in kiln temperatures. A sintering belt has been used in Germany. The traveling grate seems to be the process that has received the most attention in this country (pilot operation only), and is reported to be easily controlled, and to produce a satisfactory lightweight aggregate, although requiring more maintenance, and more fuel or higher carbon fly ash than the other processes.

A study and evaluation of the various processes is badly needed; some development work will undoubtedly be required to permit a transition from the sintering pilot plants presently available to smooth commerical production. In addition, some research and testing will be needed to develop the physical properties, mixes, and other data regarding the advantages and comparisons of fly ash lightweight aggregate with existing lightweight aggregates, so as to provide reliable background information.

A decided advantage in the use of fly ash in the production of lightweight aggregate is that aggregate sintering plants can be located adjacent to power plants to reduce handling of fly ash, and block plants can be located at the same sites also. Lightweight aggregate for structural concrete can be shipped within an economical transportation radius from such strategically located centers of production.

Lightweight construction is on the increase at a tremendously accelerated rate, whether in the form of building blocks, structural concrete, partitions, or roofing slabs. Even precast and prestressed concrete producers are beginning to awaken to the advantages of lightweight concrete in their products.

Inasmuch as there is a ready, constant, and increasing market for both lightweight building blocks and structural lightweight concrete in every section of the United States, fly ash lightweight aggregate will provide a very advantageous outlet for the disposal of large quantities of fly ash, in an essentially constant year-round operation.

Statistics, on the tonnage of lightweight aggregate used in various classes of work, are practically impossible to establish. The Minerals Yearbook for 1957 indicates a lightweight aggregate production of 7,100,000 tons. With the tremendous increase in the last few years, this tonnage may be close to 10,000,000 by now. A safe estimate is 8,000,000 to 10,000,000 tons per year. About two billion building blocks (8" x 8" x 16" equivalent) were produced in 1958, and of these, 56 percent, or 1.12 billion units utilized lightweight aggregate. About 1,000,000 tons of lightweight aggregate were used in structural concrete the same year.

These figures, rough as they may be, are a good indication of the potential in the field of lightweight aggregates.

If fly ash could capture, in the long run, about ⅓ of the lightweight aggregate production, it would result in the utilization of 3,000,000 tons of fly ash. Fly ash of relatively high carbon content and low fineness, that cannot find a ready market as a pozzolan, would most likely fit this application. Thus, lightweight aggregate from fly ash represents not only a large potential tonnage, but a tonnage of material that may be unsatisfactory for many other applications.

Each cubic yard of lightweight concrete, whether in the form of building blocks, structural concrete, precast units, or prestressed members, would utilize about one ton of lightweight aggregate (a little less for high strength structural members, and a little more for blocks), which is about 5 to 8 times the amount of filler in a cubic yard of bituminous concrete (250 to 400 pounds), and about 13 to 20 times the amount of fly ash used as a pozzolan in regular concrete mixes (100 to 150 pounds) (234).

It is evident from the foregoing that this field represents the largest single untouched potential outlet for fly ash.

Research and development are needed on this facet of fly ash utilization in order to develop data and information with which to meet the already established intense competition in the lightweight aggregate field.

PORTLAND CEMENT CONCRETE

This is the field in which most of the development on fly ash has been done, and for which there is a mass of data available.

The available information indicates that, in general, when fly ash is used in the mix, it improves many of the properties of the concrete. Summarizing his experience on Bureau of Reclamation work with fly ash, Blanks stated (48):

> "On the whole, the use of fly ash resulted in concrete of quality equal to or superior to that obtained with portland cement."

Actually, this statement sums up experience with fly ash all over the world. In the United States most experience, conclusions, and this evaluation relate to air-entrained concrete, while most evidence is that European practice has not used air-entrainment as widely.

The following well-established improvements to portland cement concrete by the use of fly ash are obtained in varying degree, depending on the sources of the fly ash, the cement (60), admixtures, and aggregates, and the proportions in which these are used in the mix:

1. Superior pozzolanic action.
2. Reduced water demand (for fly ash with low carbon and high fineness).
3. More effective action of water-reducing admixtures.
4. Improved workability.
5. Reduced segregation.
6. Reduced bleeding.
7. Slower set, but well within standard limits.
8. Reduced heat of hydration.
9. Reduced drying shrinkage.
10. Reduced thermal volume change.
11. Increased extensibility.
12. Retarded autogenous shrinkage at early ages.
13. Improved molding qualities and mold wear.
14. Increased ultimate compressive strength.
15. Increased tensile strength.
16. Increased ultimate flexural strength.
17. Increased ultimate modulus of elasticity.
18. Decreased permeability and leaching.
19. Reduced alkali-aggregate reaction.
20. Reduced cement-aggregate reaction (in sand-gravel aggregate areas).
21. Satisfactory freezing and thawing resistance when used with air-entrainment (after adequate curing).
22. Indications of improved freezing and thawing resistance of mixes containing calcium chloride.
23. Improved resistance to sulfates.
24. Reduced cost due to the ultimate cementing value through pozzolanic action which permits reduction in the more expensive portland cement.

To be considered also are some disadvantages, and some suspected weaknesses of fly ash concrete as compared with plain concrete, which may be summarized:

1. Difficulty of handling fly ash as a separate material which runs like "liquid smoke."
2. Extra effort in batching and control of an additional ingredient in the concrete mix.
3. Reported difficulty in finishing when very high fly ash proportions are used (probably can be eliminated by proper adjustment of the mix).

4. Lower early strength (can be compensated for by present-day knowledge, but such compensations have not become widely known as yet).
5. Possibility of reduced surface abrasion resistance.
6. Possibility of reduced resistance to freezing and thawing if moist curing is not long enough, and if drying at early age occurs (this depends on length of moist curing period, and severity of drying action).
7. Possibility of reduced resistance to de-icing salts.
8. Possibility of higher creep in prestressed concrete.

Handling of Fly Ash

Equipment for handling fly ash without the difficulties encountered in the past is now available when operations are large enough or permanent enough in nature to justify the investment.

On smaller work, fly ash interground with the cement clinker and marketed as one product is the answer. An added advantage of such a product is the improved early strength—low early strength has been a deterrent factor in the acceptance of fly ash for general concrete use.

Finishing Difficulties

Most of the reported difficulties are probably due to poor proportioning or adjustment of the mixes and lack of familiarity of the operators with the best manner of handling fly ash concrete. These same difficulties were encountered when air-entrainment first came into use, and again when water reducing agents were introduced, but one rarely hears of these complaints any more with air-entraining admixtures, and only occasionally with water reducing agents. In the opinion of the writer, it is just a question of the need for more widespread knowledge of fly ash mix proportioning and adjustment, and of handling fly ash concrete under different placing conditions.

Early Strength

There are at least four methods for compensating for the low early strength of fly ash concrete:

1. Addition of fly ash in amounts in excess of cement reduction.
2. Addition of trace chemicals to activate the lime-fly ash reaction (still in experimental stage, but promising).
3. Addition of water reducing admixtures to the fly ash concrete mix (very good present-day practice).
4. Intergrinding with portland cement clinker.

The last named is probably the best method, as it also takes care of the objections against separate batching and handling, and to a large extent of the possible gumminess caused by large separate additions with unadjusted mix proportions.

The development of interground fly ash cement by the French is, in the opinion of the writer, the major breakthrough that places fly ash in a most advantageous position in the whole field of concrete. This technique, by improving the early strength, removes the objections against the low strength on projects that need the early strength—practically all concrete outside of mass concrete in dams. At the same time, the higher early strength permits comparisons between fly ash concrete and plain concrete on an "equal strength" basis, instead of "equal age" basis which has been the general practice. Uniformity is also improved over separate batching on the job, and cost is probably reduced (58, 69).

The custom of comparing fly ash concrete with plain concrete on an "equal age" basis was a natural early development in the use of fly ash in concrete dam work, where early strength is of little importance, and where the higher ultimate strength of fly ash concrete is more frequently used as a basis of comparison.

In dam work, fly ash has established itself a very enviable position. However, the practice of comparing on an "equal age" basis is illogical when applied to other structural work because fly ash concrete is a structural material that has to meet certain engineering requirements, the most important of which is strength.

Just because fly ash concrete has resulted in lower early strength in the past, is no reason why such practice should continue now that ways and means are available to improve the early strength. Thus, the argument against the lower early strength of fly ash concrete loses its validity, and fly ash becomes a satisfactory potential material for all types of construction where early strength is an important factor. A much more logical and more realistic procedure is, therefore, to compare the two types of concrete when they have reached the required engineering property for a structural material—in other words, when they have reached the same strength. It is felt that comparisons made in such a manner will provide some very striking data in favor of fly ash concrete.

Comparisons on "equal strength" basis may very well change the entire picture regarding the reports of possibly lowered resistance to salts, abrasion, and freezing and thawing, as most observations in the past have been made on fly ash specimens placed under test at the same age as the control instead of at the same strength level as the control.

Another advantage of the intergrinding of fly ash with cement clinker is that is permits marketing fly ash and portland cement as one combined material, either as portland cement (where the fly ash addition is low enough to produce a material within the regular cement specifications), or as portland-pozzolan cement (with the higher fly ash and slag additions to obtain more intense pozzolanic and other improved properties contributed by fly ash). This type of merchandising will by itself increase the potential market for fly ash tremendously, inasmuch as it opens its use to all the small jobs which cannot afford the separate fly ash handling and batching.

This would be particularly the case in buildings in which smooth surfaces and architectural details are involved—features that can be obtained more easily with fly ash concrete than with plain concrete. The large projects, centralized at one spot, such as dams, would still utilize fly ash as a separate material, and thus obtain the benefit of flexibility and leeway in adjusting mixes, as long as such work does not require the higher early strength afforded by intergrinding.

It is unfortunate that the term "replacement" has come into use and thus forced fly ash concrete into unrealistic comparisons. Structural materials should be compared on the basis of their engineering properties, irrespective of their constituents, as long as such constituents are not detrimental. Therefore, every effort should be made to direct thinking into comparing the characteristics of fly ash concrete with those of other concretes on the basis of properties and performance without reference to replacements or additions.

There is no justification or logic in pitting fly ash or pozzolans against cement in the mind of anyone. The term "replacement" has an undesirable effect on the cement producer, because he feels that a replacement takes business away from him. Actually, the two products complement each other and result, when properly used, in better and more economical concrete. In the long run, such improved concrete, irrespective of its constituents, will help all the industries that contribute to its making, and therefore its improved performance and economy will be an advantage to the cement industry, through wider usage and applications.

A statement by Davis (146) may be aptly quoted in this connection:

> "In point of fact, however, pozzolan is not a substitute for portland cement but is an extra ingredient of concrete. It is employed for the purpose of enhancing one or another of the important properties of concrete. Its use may and usually will lead to a reduction in the cement requirement, but also, depending upon the character and amount of the pozzolan employed, may and usually will lead to other changes in the concrete-mix design such as reduction in sand content."

In the case of fly ash, the mix adjustment usually also leads to a reduction in the water content, but the writer has never heard anyone calling fly ash a "water replacement."

These are the reasons why the use of the term "replacement" should be discouraged in scientific circles.

Resistance to Abrasion

The evidence of reduced resistance to surface abrasion is not too definite, although it points in this direction both in the laboratory and under observation of existing pavements. Research on this aspect is also needed.

Resistance to Freezing and Thawing

There seems to be some experimental evidence that short curing periods followed by drying reduce the acceptable freezing and thawing resistance of fly ash concrete. On the other hand, short, moist curing followed by exposure to 50 percent relative humidity air prior to freezing provides adequate resistance. A study of this evidence, compared with the apparently satisfactory service records on several experimental highway pavements in the East and Middle West, that have been in service around 10 years, and in which freezing weather is a substantial factor, raises questions regarding the apparent inconsistencies.

It is probable that the short, moist curing period prior to drying, leaves the concrete with a low strength (also possibly minute drying shrinkage cracks), and at the same time the drying stops or slows the pozzolanic action which would eventually have decreased permeability. Thus, the concrete specimens would be relatively weak and of high permeability, and easily susceptible to failure by the freezing and thawing test. On the other hand, the pavements that appear to have performed without evidence of freezing and thawing damage are in locations of relatively high air humidity and probably are in contact with moist subgrade, due to the sealing off of evaporation by the capping pavement itself. Thus, pozzolanic action leading to higher strengths and lower permeability is likely to continue. This, coupled with the less severe natural freezing and thawing cycles, as compared to laboratory cycles, may account for the satisfactory performance. Another factor, that may have an important bearing on the available data, is the difference between the comparatively lean mixes used in the laboratory work, and the richer mixes in the pavements. The resistance to freezing and thawing is of importance to both paving and exposed structural work, where normal curing is for relatively short periods. Research to develop reliable data on this problem is definitely needed.

Resistance to Salts

The resistance to de-icing salts has been investigated, but the results have been inconclusive and the evidence contradictory in some respects. Even though fly ash concrete appears to have reduced resistance to salts, the lower strength at the time of exposure to salts may be a significant factor that does not seem to have been considered. In the case of slag cements, there is some evidence that fly ash actually improves their resistance to salts.

Creep

There is recent evidence that concretes of "equal strength" have essentially the same creep properties. Therefore, the present doubt about creep of fly ash concrete, which may have been a deterrent to its wider use in prestressed units, may very well be eliminated through "equal strength" comparisons.

The effect of various curing methods, particularly steam curing, on creep needs studying as it may be an important factor in prestressing applications.

Basic Uses in Concrete

Essentially, fly ash can be used in regular concrete:

1. As an additional ingredient in the mix
2. Interground with portland cement clinker to provide a superior pozzolanic cement.

3. As a raw material in the manufacture of standard portland cement.

As a separate additional ingredient in the mix, fly ash is very desirable for the large project or for concrete product plants, where the handling and batching of an extra material do not present serious problems, and can be compensated for by the economies obtained.

Intergrinding with portland cement clinker, on the other hand, overcomes the low early strength, and eliminates separate handling and batching. It is very definitely the key to a much wider use of fly ash in concrete. Tests to check the control of the fly ash additions at the mill have been reported by Guillaume (242) and Jarrige and Ducreux (244). The "equal strength" comparisons made possible by intergrinding may not only remove some of the doubts that exist about fly ash concrete but may also show it to still better advantage in the areas in which it is already accepted as being superior to plain concrete.

There has been resistance to intergrinding in the United States, in spite of the potential improvement to concrete, and therefore eventual general advantage to all concerned. Ledyard (41), an American cement industry representative, voiced criticisms over 20 years ago regarding the industry's reticence with regard to marketing pozzolan cements:

> "Since at this time, it is quite clear that portland-pozzolan cements are serving well a definite and important need, ... it appears that the time is over-ripe when the portland cement industry should realize the importance of these implications and lend their support and talents to a complete and constructive study of the pozzolanic materials and portland-pozzolan cements.... Some who read this article may obtain the impression that the writer is not of the portland cement industry, but this is not the case. He is of the industry and has the interest of the industry very much at heart. He is concerned chiefly with having the industry turn out the very highest quality products at all times, and feels that industry has done themselves no favor by not recognizing the potentialities of pozzolans and doing something about developing them."

More recently French and British writers have commented adversely on this attitude in the United States (187, 211). It is hoped that this resistance can be overcome as objective data developed through research demonstrate the overwhelming advantages of pozzolan cements.

A more detailed study of the French experience along these lines, supplemented by research with American fly ashes and clinker, and development work to adapt methods to American industrial practices will be needed for the success of this application.

As a raw material in cement, the use of fly ash has been more extensive in Europe than in this country. Its limited use in this country, for this purpose, is perhaps due to the cheaper availability of other equally satisfactory raw materials, in some cases, and to lack of information in other cases, where fly ash may be the lower priced material. Two such applications are known to the writer, and there are undoubtedly other potential applications waiting for good and reliable engineering and cost data.

Estimates and Recommendations

The potential use of fly ash as an ingredient in concrete is very large. It is estimated that 308,000,000 barrels of cement were produced in the United States in 1958. If research and reliable information will result in the use of fly ash in ⅓ of the concrete, because of its advantages and lowered cost, and if it is assumed that ¼ of the cementitious material in this concrete can be fly ash, then the potential quantity of fly ash that can be absorbed in this application would be around 5,000,000 tons.

To realize such widespread use, research is needed:

1. To determine resistance to abrasion and, if need be, how to improve it.
2. To study French experience on intergrinding with cement clinker and find means of applying it to American practice.

3. To determine relationship between curing prior to exposure to freezing and thawing, and durability.
4. To determine resistance to salts and, if need be, how to improve it.
5. To study high temperature curing cycles and effect on strength and creep.
6. To develop data and procedures for wider use of fly ash as a raw material in cement.

Studies, research, and development can only indicate feasibilities, technical problems and solutions, and develop practical products that will perform in certain patterns. Information and data resulting from these activities will permit the practicing engineer to take advantage of fly ash in his everyday construction.

Block, Pipe, Precast, and Prestressed Units

Much of the discussion in the preceding general section on concrete applies to these products. The disadvantage of lower early strength is minimized by the higher early strength attained, due to the higher curing temperature. Autoclave curing would probably eliminate this difference completely. The utilization of interground fly ash may do so even with lower pressure steam curing. Saturated steam is essential for the pozzolanic action to proceed rapidly, and unfortunately not enough stress is placed on this factor, in the average plant.

Over-all estimates in this field indicate a yearly production of about two billion building block units (8" x 8" x 16" equivalent) and 14,000,000 tons of pipe for 1958. The precast concrete units industry manufactures such a variety of products that there is no readily available, over-all estimate of the quantities, but they must be considerable. The phenomenal growth of the prestressing industry from practically nothing in 1950 to an estimated production of close to $500,000,000 in 1959, with the eventual probability of a billion-dollar industry, indicates the rapid development of this field and the potential volume for fly ash concrete.

The present use of fly ash in these products, particularly block and pipe, is increasing, but the proportion of fly ash, where used, may not be as high as could be added advantageously. The use of fly ash in concrete mixes for precast units and for prestressed units has made little headway. This in spite of the advantages that its use presents.

Specifications that require a minimum cement content, and do not permit the fly ash to be counted as part of the cementitious material, have delayed the acceptance of fly ash in many cases, particularly in pipe, primarily because the cement saving incentive is eliminated by such restrictions.

It is evident that this is a field which offers opportunity for much wider utilization of fly ash. Most plants making concrete products of various types operate on a year-round basis, and do not have the seasonal operation disadvantage that construction work has in many sections of the country. In addition, such plants are usually reasonably close to industrial centers where fly ash is readily available.

Cooling and drying shrinkage from the elevated curing temperatures, long-time creep of steam-cured fly ash concrete (of great interest in prestressing work), effect of fly ash in block mixes on carbonation, actual strength gains under steam curing as compared to control mixes without fly ash—all such information is either absent, or what little is available is buried in the literature so that it has not become "general knowledge."

A program of research to provide adequate data, development to turn the research data into practical solutions for the man responsible for getting results at the plant, and dissemination of technical information to plant operators, architects, and engineers, all teamed together will undoubtedly help to increase the utilization of fly ash in concrete products.

Research and Development

The purpose of this section is to summarize the various suggestions regarding research, scattered throughout the report. This research is needed to develop information on various problems, or to clear some doubts regarding the use of fly ash in concrete.

Lightweight Aggregate

With lightweight aggregate as the largest undeveloped potential outlet for fly ash, it is logical that studies, research, and development be pushed at an accelerated rate, in order to permit the accumulation of data and knowledge to permit of disposing of the huge tonnage of fly ash that this field could absorb. This research should consist of a three-step program:

1. Evaluation of present-day practices in Europe, and of the pilot work done in Canada and the United States.
2. Development and adaptation to American problems, of the most promising procedures.
3. Research necessary to develop the properties, mixes, and related data as a background for concentrated promotion and sales.

Research is also needed on the possible use of lightweight fly ash aggregate, once it becomes available, in bituminous concrete mixes.

Intergrinding with Cement Clinker

Equally as important as lightweight aggregate research, is research on the intergrinding of fly ash with portland cement clinker. The advantages of fly ash in concrete mixes as a pozzolanic ingredient are already well established, and therefore results of research on intergrinding would be more readily acceptable and be usable more quickly perhaps than the research on lightweight aggregate. This again would involve:

1. Evaluation of the French work.
2. Adaptation of it to American operations.
3. Research to accumulate data with American materials, in order to develop the required promotional and sales programs.

This process eliminates separate batching and handling of fly ash, which are deterrents against its use in many instances, provides early strengths comparable to plain concrete (the presently obtained lower early strengths alone being a deterrent in many instances), and permits comparisons on an "equal strength" basis—factors of utmost importance in pavement work on highways and airports, and in structural work.

Closely allied to this field of research is further work on increasing the early strength by the addition of fly ash in excess of the amount of cement reduction.

What it amounts to is that the greatest utilization of fly ash can be made on the average run-of-the-mill job that cannot afford to handle and batch fly ash separately, by intergrinding with portland cement clinker. But on the larger job or cement product plant where a separate material can be handled properly, the most fly ash would be used by adjusting the mix to reduce both the cement and sand and thus obtain the high early strength.

Resistance to Adverse Conditions

The third important phase of fly ash research should be aimed at clearing the doubts regarding:

1. Resistance to abrasion of pavement surfaces due to the grit or sand that is used with de-icing salts, and traffic.
2. Resistance to freezing and thawing, under non-ideal curing conditions.
3. Resistance to de-icing salts.

The favorable clarification of abrasion, freezing and thawing resistance, and de-icing salts problems, would make it possible for fly ash to compete advantageously for the huge yardages of pavement in highways and airports that are being placed all over the country.

Raw Material for Cement

The research needed in this facet is to develop information and data that will permit wider use of fly ash in this application. The breadth of use will depend on competitive materials.

Precast Units

Because of the rapid development of early strength through high temperature curing, used in the production of building blocks, precast units, and prestressed units, research is needed to determine the optimum temperatures and curing cycles. Particular attention to the effect of fly ash used in such cycles as affecting creep, which is so important in prestressing work, is also needed.

Research Program

Research and development have proven to be an unbeatable team in the growth of American industry. It is a well-known fact that there is a direct correlation between research budgets of corporations and their growth. In the case of fly ash, research that will result in the solution of the various problems which have been enumerated and discussed can be the key for converting a large disposal cost into an eventual revenue of at least equal magnitude.

Weinheimer (157) has estimated that the fly ash production will be around 17,000,000 tons by 1963, and that the average disposal cost was 95 cents per ton in 1954.

The total of the estimates of potential fly ash use developed in this study add up to about ⅔ of the total 17,000,000 tons. Because the estimates are conservative, and because the various fields of application are growing at a very rapid rate, it is felt that in time these quantities will increase appreciably, and that at the same time a portion of the fly ash output will be absorbed by other applications, not covered in this study, one of the most important being soil stabilization.

In 1950, Major (68) estimated that the yearly fly ash research expenditure was about $75,000; but this was being spent by individual organizations with little or no coordination, thus reducing the effective returns per dollar.

Weinheimer's estimate of disposal cost of 95 cents per ton has risen, probably to one dollar or more, by now. Thus, the total disposal cost would be around $17,500,000.

Jarrige (243) estimates that the utilization of fly ash eventually converts the disposal cost into an equal amount of revenue. Thus, the $17,500,000 disposal cost would eventually be turned into about $17,500,000 revenue, or a net gain of about $35,000,000. The utilization of this amount of fly ash is also estimated to create another $35,000,000 in wealth divided between profit to the distributors, and savings and advantages to the users.

In other words, the possible reward of research and development can be the changing of a disposal cost of $17,500,000 into an asset of three times this amount—in other words, the creation of wealth equal to four times the disposal cost.

This is an exciting challenge to everyone concerned—a challenge that cannot be ignored.

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